# Table of Contents

# List of Figures

# List of Tables

# Executive Summary

## Introduction

The South Florida Water Management District (District) and the Florida Department of Environmental Protection (FDEP) are sponsoring the demonstration and evaluation of Supplemental, or Advanced Treatment Technologies (ATT) that could work in concert with Stormwater Treatment Areas (STAs) to reduce phosphorus (P) loadings from Everglades Agricultural Area (EAA) runoff. Such technologies may improve P removal performance by being deployed within the STA footprint, or they may be totally discrete unit processes that treat either the STA inflow or outflow waters. As part of this effort, District personnel developed a Supplemental Technology Standard of Comparison (STSOC) methodology to ensure that the ATTs could be compared on a similar performance and cost basis. This document presents the STSOC analysis for the Submerged Aquatic Vegetation / Limerock (SAV/LR) technology.

## The Submerged Aquatic Vegetation /Limerock Concept

In the submerged aquatic vegetation/limerock (SAV/LR) concept, P-enriched water first flows through a submerged macrophyte dominated wetland, where P is removed by plant uptake as well as by coprecipitation with $CaCO_3$ under high pH conditions in the water column. Phosphorus removed from the water column in SAV communities is deposited as a constituent of a relatively stable, high calcium, marl sediment. Limerock, the second component of the SAV/LR system, is deployed as a berm near the outflow region of the SAV wetland. This limerock “filter” can capture particulate P (PP), lower the water pH, and at times, add calcium (Ca) and alkalinity to the water column. We have not yet developed design parameters for the use of limerock berms for TP removal, so for this STSOC analysis we propose deploying limerock berms principally to improve the hydraulic performance of the wetland.

## STSOC Evaluation Criteria

The STSOC analysis has a structured protocol, designed to enable District engineers to compare and rank “Supplemental” or “Advanced” treatment technologies as to their technical feasibility and cost-effectiveness. Primary STSOC evaluation concepts address P removal performance, cost effectiveness, implementation schedule, and potential toxicity of the technology. Secondary evaluation criteria include feasibility and functionality of design, operational flexibility, sensitivity to natural disasters, and management requirements for any residuals produced by the technology.

## Focus of SAV/LR Demonstration Project

During this project, we collected data from several STA-1W platforms ranging from mesocosms, test cells (0.2ha), and full-scale SAV wetlands (147 ha - 930 ha) within STA-1W. This information was used to document the P removal performance of SAV/LR systems, and to define the key biogeochemical, hydraulic and ecological processes that influence the performance and sustainability of SAV wetlands.

## Submerged Aquatic Vegetation / Limerock Performance

SAV communities are a promising treatment wetland technology, in that they can thrive and provide effective P removal throughout the nutrient gradient that becomes established from inflow to outflow regions of the STAs. For this STSOC analysis, we therefore considered the use of SAV/LR systems in a Post-BMP application (direct treatment of farm runoff with [TP] of 122 µg/L), as well as in a polishing, Post-STA application (treating inflows with [TP] of 50 µg/L and lower).

Key data on Post-BMP performance of SAV/LR were collected in North Test Cell 15 (NTC-15), a 0.2 ha SAV wetland operated at a mean hydraulic loading rate of approximately 11 cm/day. During our STCOC monitoring period, NTC-15 reduced TP concentrations from 73 to 23 µg/L. Mass P removal during the calibration period averaged 2.1 g P/m$^2$-yr and the percentage of P removed by the SAV wetland was 64%. Data on Post-STA performance was obtained from Cell 4 of STA-1W, a 147 ha wetland that has supported a stable SAV community since at least 1995. Performance of this system has been exemplary, with its best performance occurring in 1998 and 1999, when it provided a mean flow-weighted outflow TP concentration of 14 µg/L. Mean TP inflow and outflow concentrations for the wetland for its entire operational period (2/1/95 - 9/30/01) were 52 and 22 µg/L, respectively. Mass P removal by Cell 4 during this period of record averaged 1.6 gP/m$^2$-yr, with a mean TP removal rate of 62%.

## Full-Scale SAV/LR Conceptual Design

Using P removal, hydrologic and hydraulic data from two principal platforms, STA-1W Cell 4 and NTC-15, our engineers developed a model, designated Process Model for Submerged Aquatic Vegetation (PMSAV), that we used to predict P removal performance and footprint requirements for SAV wetlands treating Post-BMP and Post-STA waters. Our STSOC Post-BMP design utilized an outflow TP target of 26 µg/L, based on long-term NTC-15 outflow concentrations. Our STSOC Post-STA design utilized inflow and outflow TP levels of 50 and 20 µg/L, respectively, based on performance of Cell 4 during the December 20001 STSOC verification period. We also developed a final, optimum design that achieved an outflow TP of 14 µg/L, based on the lowest sustainable effluent concentration (two year period) from both small-scale (mesocosm) and full-scale (Cell 4) SAV wetlands.

In our optimum Post-BMP SAV wetland design using historical STA-2 flow and P load data as input parameters, we assume that we can deploy a full-scale SAV wetland that exhibits good hydraulic efficiency. This is achieved by filling existing farm canals that lie parallel to flow, and installing limerock level spreaders within the footprint, perpendicular to flow. Under this scenario, the Post-BMP area requirement for an SAV wetland to reduce TP concentrations from 122 to 26 µg/L, with 0% bypass, is 3,150 acres. This area requirement is slightly less than one-half the STA-2 footprint.

For the optimum Post-STA analysis, we again assume it is possible to construct a hydraulically-efficient SAV wetland, by filling canals and deploying limerock level spreaders. The Post-STA area requirement for the SAV wetland to reduce TP concentrations from 25 to 14 µg/L, with 0% bypass, is 1,735 acres.

Because the model simulations indicate that footprint requirements of the SAV wetlands are very sensitive to hydraulic characteristics, we developed additional Post-STA and Post-BMP design scenarios with various levels of hydraulic efficiency, and varying target outflow concentrations. Two of these addressed the specific design requirements of the STSOC Post-BMP and Post-STA analyses. For the STSOC Post-BMP analysis, a SAV wetland with moderate hydraulic efficiency was calculated to require 4,375 acres to reduce inflow TP levels of 122 µg/L to 26 µg/L. For the STSOC Post-STA analysis, a SAV wetland that exhibits poor hydraulic efficiency was found to require 3,150 acres to reduce TP inflow levels of 50 µg/L to 20 µg/L. A clear result of our analyses is that there is a trade-off between hydraulic efficiency and wetland footprint. Further, it appears that improving SAV wetland performance through internal hydraulic enhancements can be more cost-effective than increasing the wetland footprint.

## STSOC Evaluation of SAV/LR Technology

### Compliance with Water Quality Criteria

Based on water quality and toxicity assessments performed during the STSOC period, outflows from the SAV/LR systems should not be toxic to downstream biota. Additionally, SAV wetlands sampled during this effort did not increase water column total mercury or methyl mercury concentrations.

### Implementation Schedule

We estimate that deployment of the SAV/LR technology within the STA-2 footprint will require 38 months. However, an additional 1 – 3 years likely will be required to achieve a fully functional SAV wetland. The duration of this startup period will depend on the existence of a suitable SAV inoculum within the footprint, on antecedent P levels in the soil (i.e., residual fertilizers) and on the location along the inflow – outflow gradient (i.e., a Post-BMP wetland will achieve outflow concentration targets sooner than a Post-STA system).

### Feasibility and Functionality of Full-Scale Design

With STA-1W Cell 4 (147 ha) and Cell 5b (930 ha), the District has demonstrated that construction and maintenance of SAV wetlands is feasible at the STA scale. Long-term functionality also has been demonstrated, since Cell 4 has proven to be robust and effective in removing TP concentrations down to long-term levels of 14 µg/L for a 2-year period

### Operational Flexibility and Sensitivity to Fire, Flood, Drought and Hurricane

Properly compartmentalized SAV wetlands will be less sensitive to wildfire and hurricanes than an emergent macrophyte-based STA. Flood resistance will be comparable to existing STAs.

Submerged vegetation will be susceptible to drought, and the recovery period for an SAV community is likely to be at least four to six weeks. By contrast, drydown may be a key strategy for consolidating sediments at the front-end of any vegetated STA community. With the exception of gradual sediment accumulation, SAV wetlands will not produce residual by-products.

### Cost Effectiveness

The 50 year present worth cost for a combination (Post-BMP + Post-STA) SAV/LR system that meets an outflow concentration of 14 µg/L, with 0% bypass, is $23,537,214 (without STA-2 costs). Including STA-2 costs in this analysis increases the present worth cost to $186,339,555. Omitting the STA-2 costs, the cost of removing P on a “per pound” basis (assuming outflow TP of 14 µg/L with 0% bypass) is $9/lb, assuming good hydraulic efficiency.

The STSOC Post-BMP and Post-STA designs, using assumptions of poorer hydraulic performance, resulted in different footprint requirements and costs. For the STSOC Post-BMP wetland design used to reduce TP levels from 122 to 26 µg/L with 0% bypass, the present worth cost (without STA-2 costs) is $4,167,704. For the STSOC Post-STA wetland used to reduce TP levels from 50 to 20 µg/L with 0% bypass, the present worth cost (without STA-2 costs) is $72,933,064.

The assumptions on which these costs are based are numerous. Some assumptions pertain to modeling (e.g., were the calibration data sets representative?), others pertain to hydraulic processes (e.g., will filling farm canals and adding level spreaders actually increase efficiency?), and finally, other assumptions are ecological and performance-related (at the full-scale, will SAV thrive and provide treatment throughout most of an STA footprint?). These and other questions remain unanswered, but are important to address in moving forward with deployment of the SAV/LR technology in the STAs.

## Conclusions and Recommendations

Information needs related to the successful deployment of SAV wetlands in the STAs are numerous. In our view, the most important are as follows:

- the sustainability and P removal effectiveness of SAV wetlands used for treating Post-BMP waters (waters with higher inflow TP levels than Cell 4) should be verified at an operational scale
- the performance benefits that our model indicates can be achieved through hydraulic improvements (farm canal plugging and limerock level spreaders) should be verified at an operational scale
- the possible detrimental effects of pulsed hydraulic loadings, with respect to stagnation and high peak loadings, should be assessed at an operational scale
- because water availability will strongly influence the ability to deploy SAV at an operational scale (and also influence the resulting SAV footprints), factors that influence water budgets (e.g., seepage, potential water availability during droughts) should be quantified for each STA
- large-scale assessments of drydown and reflooding on SAV sustainability and performance should be performed
- hydrilla is proving to be an effective competitor in full-scale SAV communities. Its P removal performance therefore should be quantified.
- our findings on SAV performance (all performed at STA-1W) may not be transferable to the other STAs, due to basin-specific differences in soils and inflow water chemistry (e.g., P speciation, calcium content). Key biogeochemical and ecological factors that can influence SAV sustainability and performance should be addressed for each STA.

In moving forward with the SAV/LR technology, we also recommend that the District utilize the STA-1W western flow path (Cell 2 – Cell 4) to provide “Proof of Concept” assessment of the effectiveness of hydraulic improvements (level spreaders), and of the performance and sustainability of large-scale SAV communities for Post-BMP treatment.

# Section 1: Introduction

## 1.1 Project Background

This document describes a Standard of Comparison of the submerged aquatic vegetation/limerock (SAV/LR) technology, one of several Supplemental Technologies being evaluated for enhancing the phosphorus (P) removal performance of the Stormwater Treatment Areas (STAs). This Supplemental Technology Standard of Comparison (STSOC) effort is part of a larger demonstration project, in which we addressed key biogeochemical and hydraulic wetland processes, as well as design and management protocols pertaining to the SAV/LR technology. This project and the preparation of this report was funded in part (30%) by a Section 319 Nonpoint Source Management Program grant from the U. S. Environmental Protection Agency (US EPA) through a contract with the Stormwater/Nonpoint Source Management Section of the Florida Department of Environmental Protection.

### 1.1.1 Overview of Submerged Aquatic Vegetation/Limerock Technology

The SAV/LR technology was developed by DBE in the early 1990s (DBE, unpublished data). In the original SAV/LR concept envisioned by DBE scientists, P-enriched water first flows through a submerged macrophyte dominated wetland, where P is removed by plant uptake as well as by coprecipitation with $CaCO_3$ under high pH conditions in the water column. Effluent from the SAV system is fed through a limerock bed, where the limerock surfaces act as a nucleating site for further P coprecipitation with $CaCO_3$. The limerock also serves to reduce the pH of the wetland outflow water.

In the Phase I mesocosm assessment (1998 – 1999) sponsored by the District and FDEP, we demonstrated that SAV wetlands indeed are very effective for water column P removal. Additionally, in our Phase I efforts we observed that the SAV community appears to form a relatively stable, high calcium (Ca) sediment. In contrast to our original hypothesis, however, the back-end limerock filter appears to capture particulate P (PP), rather than serve as a nucleation site for coprecipitation of soluble reactive P (SRP). Under high hydraulic loadings, some of the PP sequestered by the limerock is converted to SRP, which is then exported from the filter. SRP export from limerock filters under low TP loadings appears minimal. Based on these Phase I findings, we elected to construct limerock berms in two 0.2 ha test cells, just upstream of the outflow, where the SRP produced in the limerock filter can be assimilated by a small downstream SAV community. The performance of both of these wetlands, North Test Cell 15 (NTC-15) and South Test Cell 9 (STC-9), is evaluated under this STSOC.

The final platform used for the present STSOC evaluation is the 147 ha Cell 4 of STA-1W, which was one of the original four wetlands that comprised the Everglades Nutrient Removal (ENR) Project. The locations of the test cells and Cell 4 in STA-1W are shown in Figure 1-1. Upon completion of ENR construction in the early 1990s, a scientific Technical Review Panel established by the District recommended that emergent macrophytes in Cell 4 be controlled

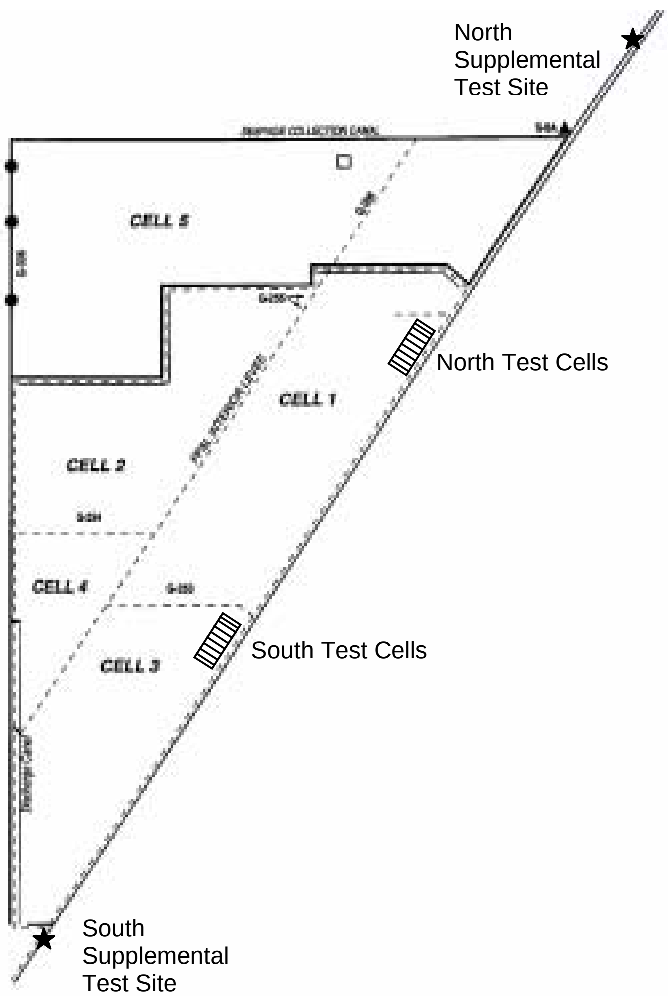



**Figure 1-1.** Map of STA-1W Assessment Sites

with water levels and herbicides so that a “periphyton-dominated” community could develop (Kadlec et al, 1991). The report stated: “The final element in the full-scale ENR project (Cell 4) should be focused on lowering P concentrations to values below those normally found in dense macrophyte stands. Thus the downstream polishing area should be designed and operated to promote algae, including pristine Everglades periphyton species, and associated (sparse) macrophyte communities. The mechanisms of P removal in this cell are anticipated to involve algae-mediated calcium and carbon chemistry. Establishment of such an ecosystem will require initial deep flooding, and maintenance may be necessary to avoid unwanted species. It should also be noted that while the polishing area would contain algae and possibly floating-leaved plants, it may not be possible to duplicate the pristine Everglades ecosystem in the polishing cell".

The District technical staff implemented this recommendation, and has monitored the performance of Cell 4 along with the other three ENRP Cells since September 1993. Several findings from Cell 4 have proven important to the future performance enhancement of the STAs. First, SAV colonization in Cell 4 demonstrated that large-scale treatment wetlands created from farm fields do not necessarily have to be dominated by cattail. Prior to this experience, it was widely held that at the enormous spatial scale of an STA, little could be done to discourage dense cattail stands. Second, a stable, diverse submerged plant community has developed and persisted in Cell 4 since 1994 or 1995. While SAV dominance was not predicted, this community has performed well, exhibiting a P settling rate substantially higher than that of the other ENR Cells (Chimney et al. 2000). District and DBE personnel have performed extensive monitoring and biogeochemical and hydraulic investigations in Cell 4, and much of these data form the basis for the present STSOC analysis.

## 1.2 Summary of SAV/LR Experimental Design and Treatments

The ability of the Stormwater Treatment Area (STA) wetlands, along with associated wetland-based “Supplemental Technologies”, to meet the Post-BMP water treatment goal of 10 µg/L is complicated by the fact that the Post-BMP waters contain a mix of P species, namely soluble reactive P (SRP), dissolved organic P (DOP) and particulate P (PP). Our analyses of the Post-BMP runoff influent to the STA-1W from June 1998 – May 2001 revealed an average [TP] of 104 µg/L, with SRP the dominant fraction (49%), followed by PP (36%) and DOP (15%). Our “Phase I” findings demonstrated that the SRP fraction is readily removed by SAV communities, while the DOP and PP fractions are more recalcitrant. Even though the wetland sediments are the ultimate P sink, they, in addition to the standing crop of vegetation, can return each of these P fractions back to the water column. Moreover, transformations among the P fractions (between “labile” and “recalcitrant” forms) can occur along the P concentration gradient that is established in the treatment wetland (Figure 1-2).

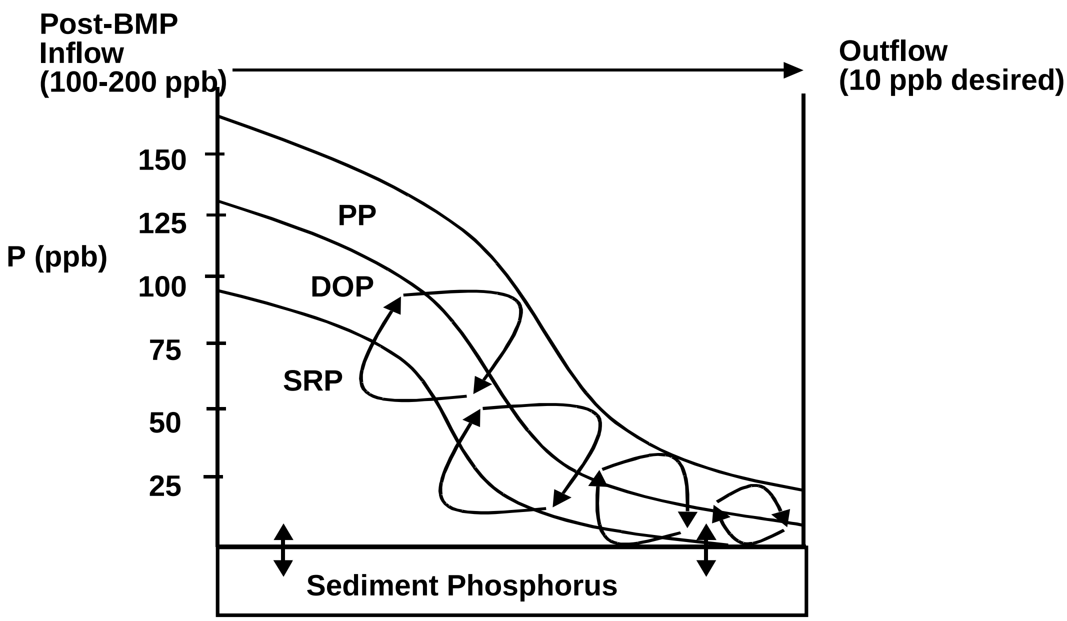



**Figure 1-2.** Schematic depicting changes in concentration of P Species (PP = particulate P; DOP = dissolved organic P; SRP = soluble reactive P) as water passes through an STA wetland. Sediments may act as a P source or sink, and cycling of P forms may occur throughout the wetland.

The task of harnessing large-scale stormwater treatment wetlands to produce extremely low outflow P concentrations is unprecedented, and it is our team’s belief that a sustainable, optimized wetland treatment system can only be achieved through an understanding of key wetland processes. The basis of our Phase II demonstration effort therefore was to gain a greater understanding of the following key processes of SAV wetlands and limerock filters.

- **Biogeochemical Processes**: What are the mechanisms by which SAV systems remove water column P to low levels? Additionally, what can be done to encourage these processes?
- **Hydraulic Processes**: We observed in our Phase I effort that large-scale STA cells are prone to hydraulic inefficiencies. In Phase II we initiated efforts to define the significance of these inefficiencies on treatment performance, and to suggest techniques for improving system hydraulics.
- **Ecological Processes**: Can SAV wetlands be built on a large scale along the 120 – 10 μg/L total P gradient, and can they be maintained along this nutrient gradient under conditions of varying flows, depths and drought?

The first two components were the focus of our demonstration program and modeling efforts. We obtained information on ecological processes primarily from direct observations of SAV communities throughout the STA-1W wetlands.

For our Phase II effort, we performed a suite of assessments using laboratory, microcosm, mesocosm, pilot-scale and full-scale platforms. A brief synopsis of each Phase II evaluation is provided below. Key findings from these assessments that pertain to the STSOC analysis and the engineering scale-up are described later in this document.

### 1.2.1 Microcosm and Laboratory Assessments

*Effects of Calcium/Alkalinity and Soluble Reactive P Concentrations on P Coprecipitation in SAV Wetlands*

We performed two outdoor microcosm evaluations to assess the effects of calcium and alkalinity levels on SAV phosphorus removal performance. Artificial nutrient media, rather than site waters, were used for this effort, due to the difficulty in achieving the desired Ca/alkalinity ranges with STA-1W waters. In the first assessment, “P-enriched” and “P-deficient” *Najas guadalupensis* were subjected to high SRP concentrations but varying levels of Ca and alkalinity in a short-term batch evaluation to define the relative importance of SAV uptake vs. coprecipitation in reducing P concentrations in the water column. In our second assessment, *Najas* was inoculated into microcosms containing combinations of high and low SRP and Ca/alk concentrations. This flow-through assessment was performed over a 3-month period, and was designed to facilitate our understanding of the chemical conditions (e.g., pH, alkalinity, Ca and SRP concentrations) that promote P coprecipitation. In this evaluation we also assessed the quantity and composition of the deposited sediments.

*Particulate Phosphorus and Dissolved Organic Phosphorus Characterization and Stability*

For this effort, we performed laboratory characterizations of particulate phosphorus (PP) and dissolved organic phosphorus (DOP) collected from ENRP Cell 4, test cells, and mesocosm waters. In one assessment, DOP and PP size fractions isolated from Cell 4 locations were analyzed for enzymatic SRP release, and SRP release under low pH and redox conditions. In a second assessment, alkaline phosphatase activity in ecosystem compartments (sediment, detritus, surface water, and biomass) was analyzed using bench-scale incubations. Finally, PP isolated from SAV and cattail communities inhabiting the inlets and outlets in the test cells and Cell 4 was characterized and compared to assess PP transport and degradation characteristics.

### 1.2.2 Mesocosm Assessments

*Impact of Fluctuating Water Depths on SAV Phosphorus Removal Performance*

During full-scale operation, the STAs will be subjected to a variable depth regime, with projected depths ranging from 0 to 1.3 m. During our Phase I evaluations, we found little difference in P removal performance by SAV mesocosms that received Post-BMP runoff at a 10 cm/day HLR, and operated at steady state water depths of 0.4, 0.8 and 1.2 m. For the current assessment, we subjected SAV in these mesocosms to a fluctuating depth regime by changing the water depths every five weeks to assess impacts on P removal.

*Impact of Vegetation Harvest on SAV Performance*

During Phase I, we subjected SAV in mesocosms to a regime of periodic (annual) harvest. For this effort, we continued operations of the mesocosms on Post-BMP waters for several more months, and performed an additional harvest to assess the impacts of harvesting on P removal performance.

*Long-Term Monitoring of SAV Performance*

During Phase I, we initiated an evaluation (on June 1998) in which sequential SAV wetlands and limerock reactors received Post-BMP waters under three separate hydraulic loading regimes (11, 22 and 53 cm/day HLRs). For this effort, we continued operation of these mesocosms to assess long-term performance, and to assess the ultimate fate of sequestered P among the ecosystem compartments (sediments and vegetation).

*Hydraulic Pulse-Loading Impacts*

Hydraulic loadings to the STAs will average about 2.6 cm / day. However, the range of flows will vary widely, with extended periods of no flow interspersed with peak flows in excess of 20 cm / day. We used mesocosms to predict the impact of a pulsed flow regime on SAV performance. Mesocosms that previously were operated with Post-BMP waters under steady-state hydraulic loading conditions were supplied with a "pulsed" HLR regime that mimicked the dynamic STA-2 inflow data set. This 40+ week pulsed regime included periods of stagnant (no flow) conditions, as well as periods of extremely high flows. Performance of the pulsed systems was compared to that of SAV systems operated under steady-flow conditions.

*Drawdown – Reflooding Impacts on SAV Wetlands*

Our review of the long-term STA-2 flow data set suggests that during extremely dry years, at least a portion of most STAs will totally dry down. Because impacts of drydown are unknown, we performed a mesocosm evaluation to assess drydown impacts on the SAV community and associated sediments. We utilized mesocosms that had received Post-BMP waters under two separate HLRs (11 and 55 cm / day). These mesocosms were dried-down for 105 days. Sediment compaction was assessed over time during drydown, and P-removal / export was evaluated upon re-flooding.

*Sequential SAV/LR Systems*

During Phase I (October 1998), we established a series of sequential systems (deep SAV followed by shallow SAV followed by LR filters) that were operated under steady HLR conditions, receiving Post-BMP waters. We continued operation of these systems for several months into the Phase II period.

*Performance of Cattail vs. SAV*

During Phase I (October 1998), we established a pair of cattail mesocosms to provide a performance comparison with adjacent SAV mesocosms. All mesocosms were operated at a 10 cm / day HLR (Post-BMP waters) and at a water depth of 0.4 m.

*Shallow, Low Velocity SAV/Periphyton/Limerock Systems*

During Phase I, we established three very shallow (9 cm deep) SAV/periphyton/LR raceways. These systems, receiving Post-STA waters, achieved a relatively consistent 10 µg/L outflow concentration (inflow TP concentration averaged 18 µg/L) since October 1998. For this effort, we continued operation of these raceways under varying HLR conditions.

*Effect of Flow Velocity on P Removal by Shallow, SAV/Communities*

We utilized the shallow SAV periphyton raceways to evaluate effects of flow velocity on P removal performance.

*Growth of SAV in Post-STA Waters on Muck, Limerock, and Sand Substrates*

Due to concern over the need for an initial, stable substrate in "back-end" SAV communities, we established SAV communities on three substrates (muck, limerock, sand) during Phase I. We continued operation of these mesocosms during Phase II, during which time they received varying hydraulic loadings of Post-STA waters.

*Effect of Filter Media Type on P Removal Performance*

We established outdoor small-scale filter columns and beds to evaluate the P removal effectiveness of different sizes of limerock, as well as other filter media. These systems were evaluated using Post-STA waters.

### 1.2.3 STA-1W Test Cell Assessments

*Test Cell Hydraulic Characteristics*

Prior to the onset of long-term performance monitoring, we evaluated the hydraulic characteristics of north and south test cells under varying depth and flow regimes by conducting dye tracer studies.

*Test Cell Modification and Long-term Monitoring*

At the north bank of test cells, a limerock berm was designed and installed perpendicular to flow 90% down the length of NTC-15. NTC-1 was operated as a control. At the south test cells, a limerock berm was installed perpendicular to flow 90% down the length of STC-9. STC-4 was operated as a control. We monitored P removal performance of the test cells for slightly more than one year, to generate a data set for the District's Standard of Comparison. Sediment accrual and characterization measurements were performed on each test cell during late 2001.

### 1.2.4 STA-1W Cell 4 Assessments

*Cell 4 Dye Tracer Studies and Hydraulic Optimization Analysis*

We performed two hydraulic tracer assessments in Cell 4. During both assessments, we performed measurements along internal transects as well as at inflow / outflow locations. Time-sequenced maps of spatial dye and total P concentrations, as well as conventional calculations of mean residence time and residence time distribution plots, were used to assess opportunities to improve Cell 4 hydraulics.

*Cell 4 Performance Monitoring*

We performed internal sampling in Cell 4 to spatially characterize accrued sediment and live SAV biomass. Intensive water quality monitoring at inlet / outlet stations, as well as along internal transects, enabled us to interpret performance under varying HLR and depth conditions.

*Cell 4 Sediment P Stability and Characterization*

We performed three types of assessments and analyses to characterize Cell 4 inflow and outflow region sediments. First, we exposed sediments to low and high pH, low redox, low SRP and Ca concentrations, as well as desiccation followed by reflooding. In a second assessment, we performed inorganic and organic P fractionations to assess P allocation among the various chemical pools and labile / nonlabile forms. Third, we deployed porewater equilibrators to define porewater P concentrations and to quantify diffusion gradients across the sediment-water interface.

### 1.2.5 STA-1W Cell 5 Assessments

*Cell 5 SAV Recruitment and Inoculation Evaluations*

As a result of our Phase I efforts, we recommended to the District that STA-1W Cell 5 be flooded quickly in order to establish SAV communities. To evaluate the rate of SAV colonization in this wetland, we established a vegetation monitoring grid of 120 stations. A semi-quantitative assessment of SAV species was performed quarterly at each station. For this task we also evaluated several SAV inoculation techniques and performed an *in situ* assessment to evaluate the effect of liming on initial soil P release.

### 1.2.6 Phosphorus Process Model

In addition to the above investigations, DBE engineers and scientists developed an empirical model (Process Model for Submerged Aquatic Vegetation [PMSAV]), that we used to predict SAV performance and footprint (area) requirements.

## 1.3 Phosphorus Removal Mechanisms and Performance

In all treatment wetlands, the sediments are the ultimate repository of P removed from the water column. Wetland vegetation, whether algal or macrophyte, mediates the removal of water column P, provides a temporary storage of P, and in part controls sediment P recycling (in some cases by root uptake of sediment P (e.g., “P mining”) as well as through at least partial control of the sediment/water interface microenvironment). To achieve the greatest mass P removal per unit area (“k” value), as well as the lowest outflow P concentration, the wetland must provide the following:

- efficient mechanisms for removal of water column P
- storage of sediment P in stable forms
- water column and sediment/water interface microenvironments that encourage sediment P retention

As a basis of this STSOC analysis, we provide the following synopsis of our current understanding of SAV/LR phosphorus removal performance and selected biogeochemical, ecological and hydraulic processes.

### 1.3.1 Water Column Phosphorus Removal

A simple measure of the P removal performance of SAV communities can be determined by assessing inflow and outflow water quality data. Our first long-term SAV phosphorus removal assessments using Post-BMP waters were initiated in 1997 using outdoor microcosms. We found that SAV communities operated at a high hydraulic loading rate (24 cm / day HLR) and a short hydraulic retention time (1.6 day HRT) could provide effective P removal, reducing TP concentrations from 84 to 30 µg / L, with a average mass P removal rate of 4.8 g P / $m^2$-yr over a 20.5 month period (Dierberg and DeBusk, unpublished). As our monitoring efforts were scaled-up to larger platforms (i.e., mesocosms, 0.2 ha test cells) we found the same consistent trend: for Post-BMP waters, which contain a high percentage of labile P (e.g., SRP), rapid P concentration reductions occur in SAV communities. An attractive feature of SAV communities is that rapid depletion of SRP occurs at a high HLR, which indicates that the area requirement needed to achieve such a reduction may be low. For example, the test cell performance (NTC-15) documented in Table 1-1 was achieved at an average HLR of approximately 11 cm / day. The long-term average STA HLR loading is projected to be 2.6 cm / day. Therefore, the NTC-15 performance is approximately equivalent to performance attainable under steady-state conditions using the first 21% (2.3 / 11 X 100%) of the STA footprint. This is a rough approximation, of course, because full-scale STA factors such as hydraulic inefficiencies and inflow pulsing may adversely influence performance, but it still gives an indication of the effectiveness of the SAV community for removing P from Post-BMP waters.

**Table 1-1.** Phosphorus removal performance of several SAV systems used to treat "Post-BMP" and "Post STA" waters.

| | | | | Total Phosphorus | | |
|---|---|---|---|---|---|---|
| | Platform | # Days | HLR (cm / day) | Inflow (µg / L) | Outflow (µg / L) | Mass Removal Rate (g / $m^2$ / yr) |
| Post BMP | L2 Mesocosm | 1086 | 11 | 101 | 25 | 2.9 |
| | M2 Mesocosm | 1086 | 22 | 93 | 31 | 5.5 |
| | S2 Mesocosm | 1086 | 53 | 96 | 51 | 8.7 |
| | NTC-1 Test Cell | 419 | 13.7 | 69 | 24 | 2.4 |
| | NTC-15 Test Cell | 419 | 10.8 | 72 | 23 | 2.1 |
| Post-STA | STC-4 | 420 | 5.6 | 26 | 22 | 0.1 |
| | STC-9 | 420 | 5.8 | 28 | 21 | 0.1 |
| | Cell 4 (10 / 97-9 / 99) | 720 | 11.3 | 38 | 14 | 1.1 |
| | 'Muck' Mesocosm | 866 | 15.9 | 23 | 14 | 0.5 |

Phosphorus removal rates within the SAV communities decline markedly once the labile P forms in the water are depleted. Phosphorus removal performance of several SAV systems used to treat "Post STA" waters are depicted in Table 1-1, where we provide performance data from different platforms, and different operational periods. Note that mass P removal rates are substantially lower than those achieved under Post-BMP conditions. These SAV systems occasionally have achieved 10 µg/L outflow concentrations, but performance to date at this level has not been consistent. The best long-term performance has been attained by Cell 4, which achieved a flow-weighted outflow average TP concentration of 21 µg/L over its entire operational period, an outflow mean of 14 µg/L over two years, and a mean of 12 µg/L for one year. In STA-1W, SAV wetlands therefore appear to readily achieve an outflow TP concentration of 20 µg/L, and can attain average levels of 15 µg/L for several years. Achieving long-term outflow levels of 10 µg/L, however, is much more challenging.

The reasons behind the difficulty in achieving the 10 µg/L "target" are complex, and likely involve both external runoff characteristics and internal wetland processes. As an example, DOP and PP are generic, operationally-defined terms of water column P forms, and provide no useful information either as to the nature of the constituents, or about their ultimate bioavailability. Indeed, it could be that the variations in TP outflow concentrations observed in most SAV platforms are due to changes in the characteristics of the DOP and PP entering the STA as Post-BMP runoff, or due to temporal changes in internal loading of DOP and PP within the SAV wetland.

### 1.3.2 Sediment Phosphorus Accrual

Whether directly assimilated by plants or co-precipitated and settled, the sediment is the ultimate P reservoir in a SAV wetland. All of our monitored platforms demonstrated an accumulation of high Ca, "marl" sediments (16 – 21% [Ca]), with Cell 4 sediment [TP] ranging from 1270 mg/kg (inflow region) to 582 mg/kg (outflow region). Undoubtedly because of higher productivity, the inflow region also has exhibited a greater accumulation of sediments (e.g. 1.8 vs 0.5 cm/yr for inflow and outflow regions of Cell 4).

For most SAV wetland platforms, a reasonable percentage of the observed mass of P removed from the water can be accounted for in the sediments. Mesocosms that received Post-BMP runoff at HLRs of 11, 22 and 55 cm/day exhibited mean water column P removal rates of 2.9, 5.5

and 8.7 gP/$m^2$-yr over a 36 month period. For these respective treatments, we recovered 79, 62 and 60% of this “removed P” in the sediments. Based on an average of a small number of inflow and outflow sediment cores, we estimate that Cell 4 has stored sediment P at a rate of 1.1 gP/$m^2$-yr. This compares reasonably well to the mean observed water column removal rate of 1.6 gP/$m^2$-yr since early 1994.

### 1.3.3 Ecological Processes

In our monitoring and evaluations performed using several platforms in STA-1W, we observed fairly diverse SAV populations along the entire 120 – 10 µg/L TP gradient. *Najas guadalupensis* (southern naiad) is the most ubiquitous species in the large-scale STA-1W wetland cells, occurring throughout the length of the nutrient gradient. *Ceratophyllum demersum* (coontail) occurs primarily in the inflow and mid-regions, whereas at the large-scale, *Potamogeton pectinatus* (pondweed) occurs only near the outflow region of Cell 4. At the test cell wetlands, *Chara zeylanica* (stonewort) dominated both north and south banks. *Najas* also occurred in the test cells in smaller populations. In mesocosms that received Post-BMP waters, *Ceratophyllum* dominated the inflow regions, *Najas* the mid-regions, and *Chara* and *Najas* the outflow regions. *Hydrilla verticillata* (hydrilla) occurs in the south test cells, but has not been found in the north bank of test cells. Although Cell 5, the largest wetland in STA-1W, had little hydrilla present one year after flooding, hydrilla is now the dominant SAV species in the system.

Most of the SAV communities in STA-1W appear stable. The SAV in Cell 4 probably colonized during 1994, and as of 2002, remains robust. For this effort, we tracked colonization of STA-1W Cell 5b, a 930 ha wetland that was initially flooded during March and April 1999. Periodic sampling at 120 stations revealed the gradual spread of *Najas* and *Ceratophyllum* throughout the wetland. Soils along the banks of the relic farm canals appeared to contain *Najas* propagules, which aided in the rapid spread of this species (Figure 1-3). More recently, hydrilla has invaded Cell 5. This distribution of this species, and possible consequences of its presence, are described later in this report.

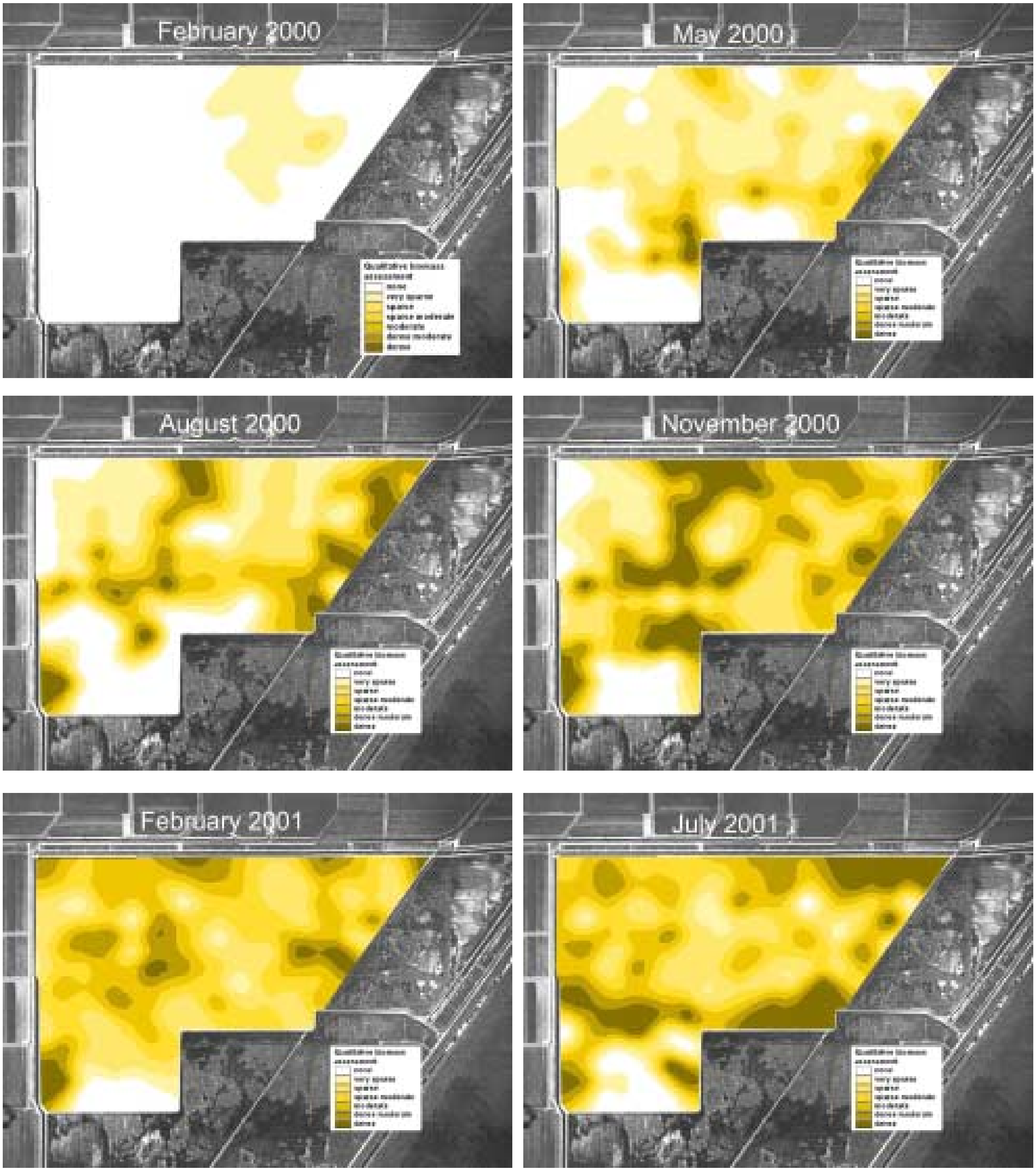



**Figure 1-3.** Colonization of *Najas guadalupensis* in the 930 ha STA-1W Cell 5b wetland. The cell was initially flooded in April 1999.

Three factors appear to cause mortality in SAV beds: shading by floating plants and floating mats of emergent plants, physical disruption by the floating mats, and rapid increases in the nutrient regime. The non-rooted species *Ceratophyllum* seems to disappear from the water column under extreme low nutrient conditions. *Chara* is the most unpredictable SAV species, forming dense mats throughout the nutrient gradient in test cells and mesocosms, but then disappearing in response to unknown environmental cues.

Our observations suggest that the level of nutrients in the water will play a key role in defining the range of the SAV communities in the STAs. At the inflow region, inorganic N and P levels often are adequate to support robust mats of floating plants, primarily water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*). As noted above, these mats can kill the SAV by shading. We have observed the mortality of SAV beds as a result of floating plant shading in Cell 5, and also in the north test cells.

The SAV species we have evaluated appear to colonize and perform well on farm soils (muck). To assess the hypothesis that a limerock substrate might be more effective than muck for attaining low outflow TP concentrations, we evaluated P removal by SAV cultured both on muck and limerock. The muck SAV community was much more robust than the one that developed on limerock, and provided comparable P removal performance (Figure 1-4). TP concentrations for inflow waters, and outflows from muck and limerock-based SAV mesocosms, were 23, 14 and 15 µg/L, respectively.

In summary, a diverse SAV community appears to thrive along the inflow-outflow concentration gradient in STA-1W. The agricultural (muck) soils provide a satisfactory substrate for SAV colonization and persistence along the length of this gradient. Floating plants are most robust at the STA inflow region because of the greater availability of macronutrients. Shading by mats of floating plants can compromise the stability of SAV at the inflow region of an STA. During high flow (and high stage) events, floating plants also can be distributed further down the length of the wetland. In the mid- and outflow regions of the STA, these floating plants, and any emergents, must be controlled to maintain the stability of the SAV communities.

SAV communities at the back-end of the STA appear quite stable, since low water column nutrients help to preclude competition from other macrophytes.

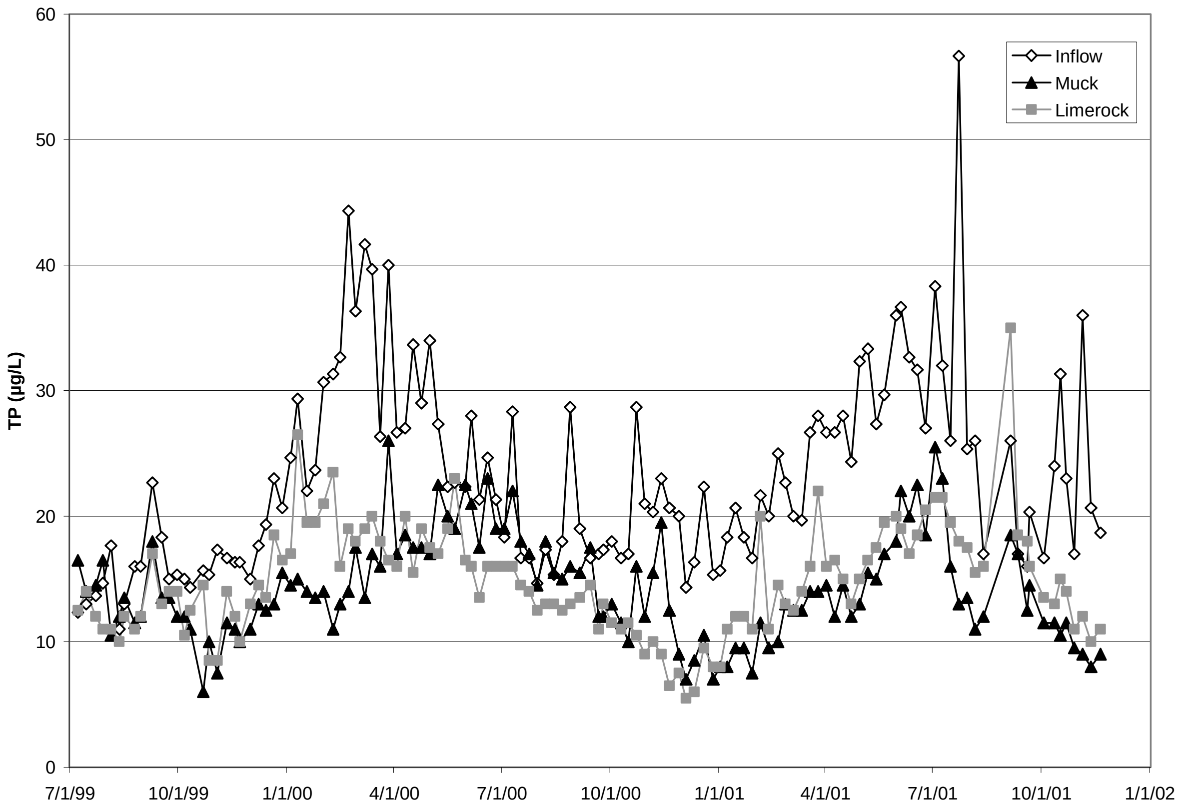



**Figure 1-4.** Inflow and outflow TP concentrations for SAV cultured in mesocosms on muck and limerock substrates. Mean HLR during the assessment was 10 cm / day.

### 1.3.4 Hydrology Issues

The STAs are projected to receive Post-BMP runoff at an average hydraulic loading of 2.6 cm / day. The day to day variations in flow, however, are expected to be pronounced, ranging from extended periods of no flow to peak flows that are as high as 15 times the average flow. It therefore is important to understand how the SAV communities perform in response to high flow pulses, as well as to stagnation (standing water, no flow) and total drydown. During Phase II, we performed two mesocosm evaluations that address SAV performance over a range of hydrologic conditions.

In the first evaluation, we subjected SAV mesocosms that previously had been operated for 1.5 years at steady-state HLRs of 11, 22 and 53 cm / day, to a pulsed hydraulic loading regime. To provide insight into pulsing effects, we summarize results herein from the 11 cm / day HLR treatment, where we provided inflows ranging from 0 to 35.2 cm / day. Note that the previous 18 month steady-state operational period at 11 cm / day corresponds to a HLR that is approximately five times the mean loading of the STAs, so that the performance exhibited by this mesocosm SAV community (with respect to outflow concentrations, and internal loading of P from sediments) is roughly analogous to performance that could be expected from the first 20% of an STA footprint. Also, to facilitate mesocosm operations and sampling during this assessment, we "averaged" the flow variations somewhat, so that the flow peaks were slightly lower, but of longer duration (typically 1-2 weeks) than would be expected for an operational STA.

The pulsing regime, and its effect on SAV performance, are depicted in Figure 1-5. This assessment demonstrates two key factors: first, that the SAV community still provides effective P removal during flow peaks, and second, that stagnant conditions at times result in higher water column concentrations than when water is flowing through the wetland. Influent TP concentrations averaged 109 µg / L during the assessment, and outflow concentrations from the pulsed and adjacent control (steady-state 11 cm / day HLR) mesocosms averaged 33 and 31 µg / L, respectively. (Note that the pulsed outflows represent mean values for when water actually was exiting the wetland). The high TP water column concentrations under stagnant conditions are almost certainly a result of internal P loading from the accrued sediments. Our other Phase II evaluations suggest that internal sediment loading will be higher at the immediate inflow region (i.e., in the first 10%, rather than 20% of the footprint), and that internal loading of sediment P declines further down footprint, towards the middle and outflow regions of the STA. The significance of elevated water column P concentrations during periods of stagnation to overall STA performance is still unclear, since no outflow occurs at this time.

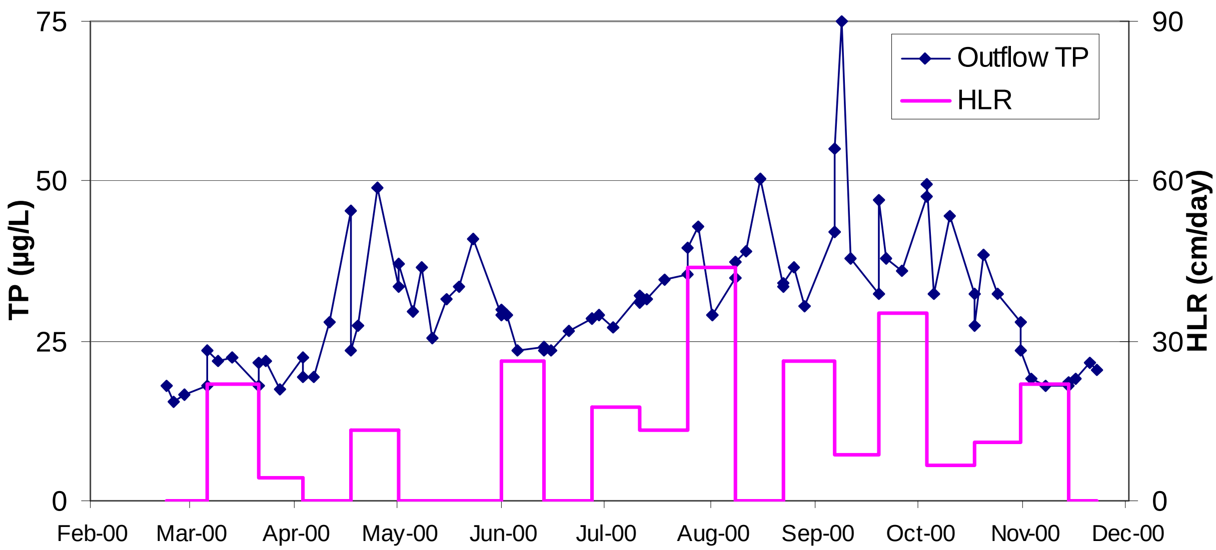



**Figure 1-5.** Outflow TP concentrations from an SAV mesocosm that received a pulse-loading of Post-BMP waters. During "no-flow" periods, values represent concentrations of standing water in the wetland. Inflow TP concentrations during this period averaged 109 µg/L.

An important issue related to the sustainability of SAV wetlands centers around the ability of the system to recover from periodic drought-induced drydown. All SAV species will quickly desiccate and die when water is withdrawn from a wetland. This brings up several concerns. First, following rehydration, can the SAV community recolonize the wetland? If so, how quickly will recolonization occur, and how soon will the SAV begin providing treatment? Finally, upon rehydration, will there be an unacceptable "flush" or export of vegetation or sediment P? By contrast, periodic drydown may be beneficial, since it likely reduces the depth of the accrued sediments by oxidation and dewatering.

To obtain some rudimentary information on drydown and reflooding impacts, we performed an assessment in which SAV mesocosms that had been operated under low and high HLRs (11 and 53 cm/day) for over two years were subjected to a 110 day drydown. During the drydown period, we measured the rate of sediment compaction in the mesocosms. Following rehydration, we evaluated P removal/export, as well as the recolonization of SAV species. A synopsis of the results of the drydown effects in the 11 cm/day HLR mesocosm is as follows.

During the 110 day drydown, all of the SAV desiccated and decomposed to the point of being unrecognizable (Figure 1-6). Sediment moisture content decreased from 88 to 70%, and sediment depth decreased by 60%, from 10 to 4 cm. We observed an initial flush of P upon reflooding, but within six weeks, the SAV had recolonized (presumably from propagules in the sediment) and mesocosms attained a good level of performance (Figure 1-7). Mesocosm inflow and outflow TP concentrations during the six weeks prior to flooding averaged 51 and 15 µg/L, and TP concentrations for these respective locations during the 8 week post-hydration period averaged 97 and 37 µg/L.  While these initial findings are promising, more investigations of drydown at a larger scale are needed, particularly with respect to the SAV recovery period, and needs for vegetation management prior to or immediately following rehydration.

**Figure 1-6.** Effect of drydown on SAV community, two weeks (left) and one month (right) after initial drydown.

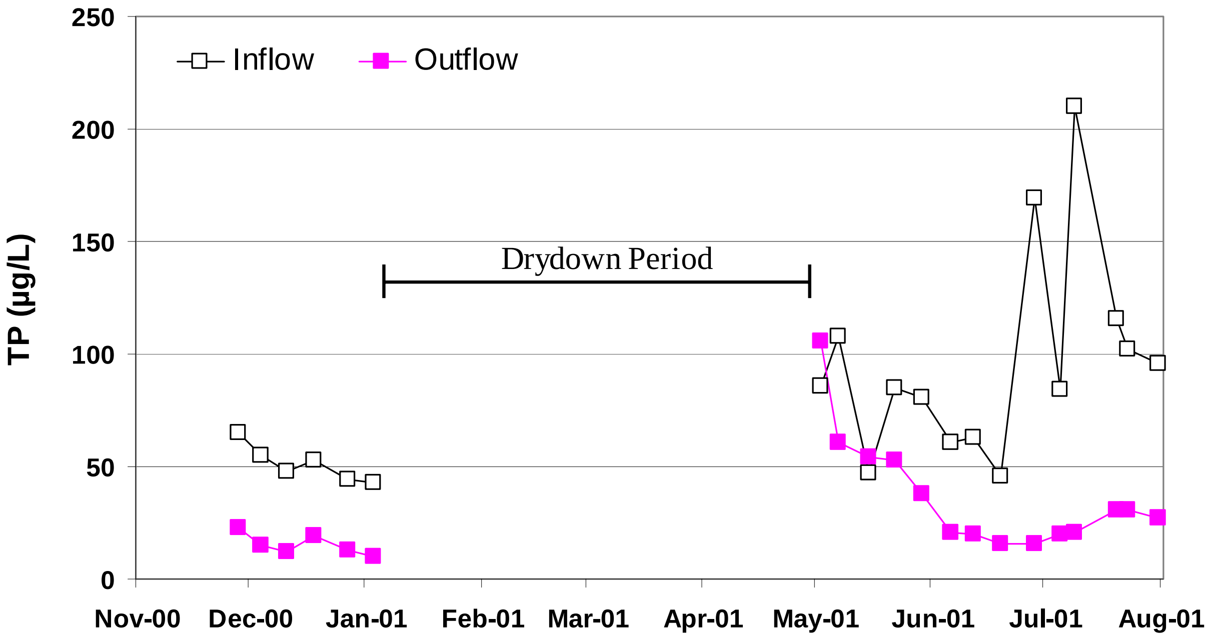



**Figure 1-7.** Effect of a 110 day drydown on P removal by a SAV wetland. Prior to and after drydown, this mesocosm received Post-BMP waters at a 11 cm / day HLR.

### 1.3.5 Hydraulic Processes

During Phase I, we identified two prominent hydraulic short-circuits in Cell 4, one each along the eastern and western levees. As part of our Phase II effort, we performed two hydraulic assessments of Cell 4, using the tracer chemical Rhodamine WT. Our analysis of the first tracer evaluation, performed in December 1999, suggested that the "levee" canals convey about 40% of the flow through the wetland (Figure 1-8). This hydraulic information was incorporated as part of our predictive modeling effort, which demonstrated that the Cell 4 tracer-response curve can be accurately modeled as a "three tank-in-series (TIS)" wetland, with a short-circuiting conveyance "canal" down the length of the wetland. We used the TIS number to parameterize the hydraulic efficiency of a wetland. The higher the TIS number, the more hydraulically efficient (i.e., closer to plug flow) the wetland becomes, and thus the more P removal achieved given a certain size footprint. Our hydraulic modeling is described in more detail in Section 4.

**Figure 1-8.** Flow short-circuiting along the eastern levee canal in STA-1W Cell 4. Aerial photo from DBE dye tracer evaluation, December 1999. Flow direction is from top of photo to bottom.

Following our initial tracer evaluation, we recommended that the District place shellrock “plugs” at various intervals along the levee canals. District engineers constructed these plugs in summer 2000, and the plugs appear to have partially reduced flow conveyance down the levee canals. However, during subsequent high-flow conditions, additional short-circuits were scoured through the soft sediments that had accumulated in relic farm canals. The role of these farm canals in flow short-circuiting was highlighted in our second tracer evaluation, performed in December 2001 (Figure 1-9). At the scale of the STAs, with flow paths several kilometers long, some hydraulic short-circuiting is bound to occur. However, we believe that there is great opportunity in improving P removal performance of STA-scale SAV wetlands by improving hydraulic characteristics. This approach is described in more detail in Sections 4 and 5.

**Figure 1-9.** Flow short-circuiting along relic farm canals in STA-1W Cell 4. Aerial photo from DBE dye tracer evaluation, December 2001. Flow direction is from upper right to lower left of photo.

### 1.3.6 Phosphorus Removal by Limerock Berms

Our Phase I effort demonstrated that upflow limerock "reactors" situated at the outflow region of SAV wetlands can provide supplemental P reduction, as well as provide transformation of particulate P to SRP. Based on these findings, during Phase II we deployed limerock berms in two test cells, NTC-15 and STC-9 (Figure 1-10). We analyzed water samples collected immediately in front of the berm, as well as at the cell outflow. The difference between the cell "pre-berm" station and "outflow" stations represents the additional P removal performance provided by the berm, in addition to the downstream SAV "polishing" wetland (approximately 10% of the cell area).

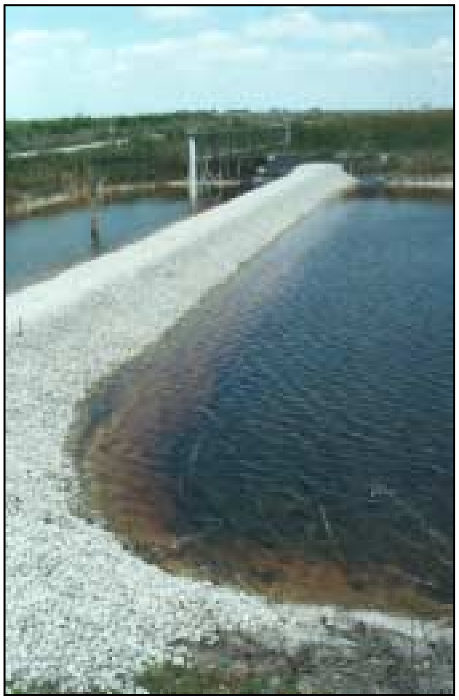


**Figure 1-10.** Outflow region limerock berm in NTC-15 deployed by DBE in spring 2000. Flow direction is from right to left of photo.

The performance of the berms differed between the north and south test cells (Figure 1-11). The STC-9 berm (& polishing wetland) performed somewhat erratically, but in general, removed about 4 µg/L of TP. The NTC-15 berm/wetland initially exported P, but over time removed considerable P, primarily as PP (Figure 1-11). No SRP was detected at the outfall location in either test cell, but it is likely that any SRP exported by the berms themselves was immediately sequestered in the downstream polishing wetland. Indeed, over time, strands of filamentous green algae developed on the downstream side of each berm, suggesting that SRP indeed was being exported from the limerock berm.

Limerock berms also likely provide a hydraulic benefit, and it is possible that their effectiveness in NTC-15 and STC-9 was due in part to hydraulic enhancements. We have incorporated limerock berms in a "level-spreader" configuration as part of our Full Scale SAV/LR Conceptual Design (Section 4).

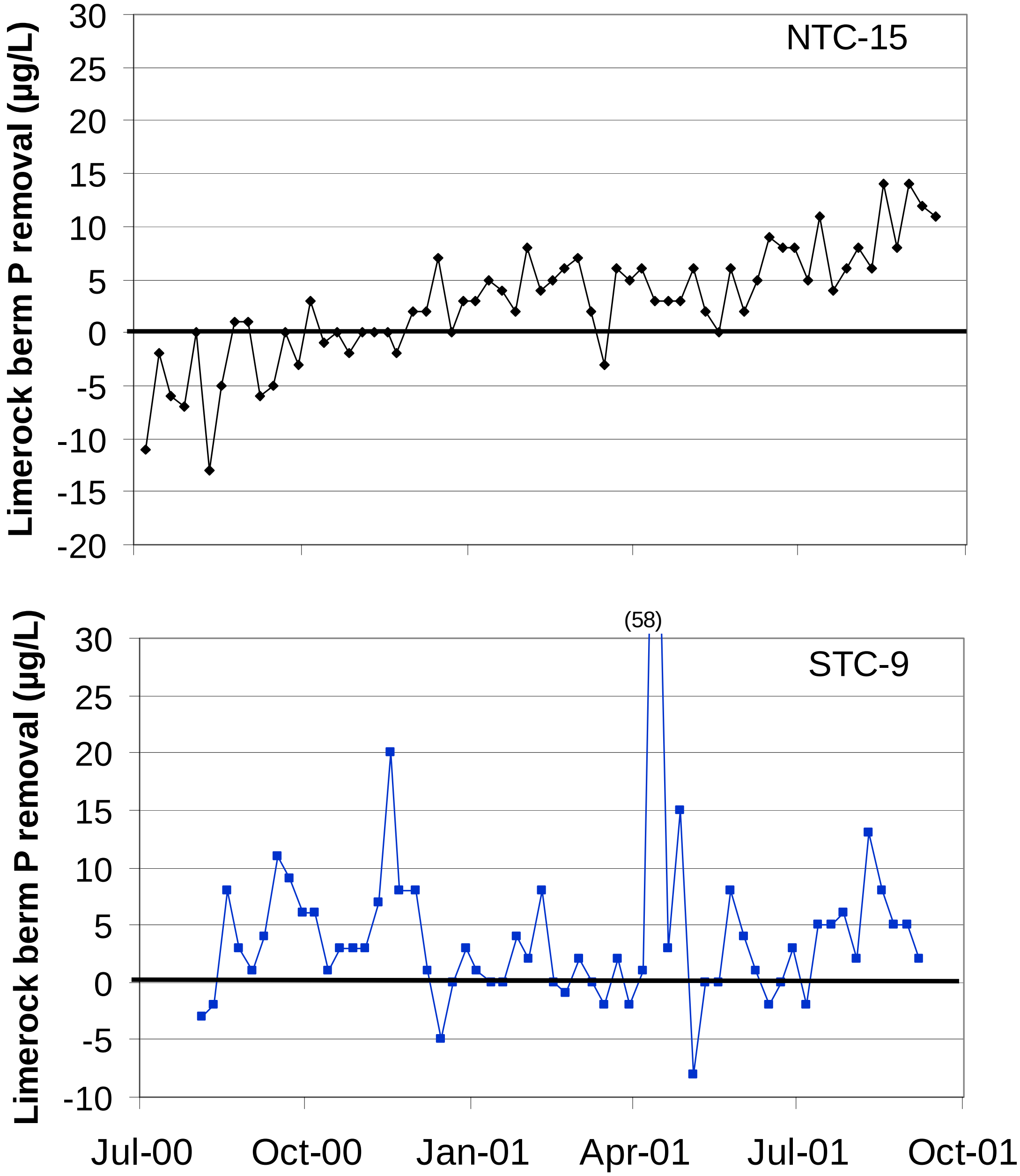



**Figure 1-11.** Total P removal provided by limerock berms (and downstream "polishing" wetlands) in NTC-15 and STC-9.

## 1.4 Standards of Comparison Methodology

The STSOC analysis has a structured protocol, designed to enable District engineers to compare and rank “Supplemental” or “Advanced” treatment technologies as to their technical feasibility and cost-effectiveness. Aspects of the STSOC that are considered primary, quantitative evaluation concepts include:

- the level of P concentration reduction achievable by the technology (based on experimental data)
- the level of P load reduction achievable by the technology (based on model data)
- cost-effectiveness of the technology
- evaluation of the potential toxicity of the technology
- implementation schedule

Other concepts addressed in the STSOC that are considered secondary, or more “qualitative”, include:

- feasibility and functionality of scaled-up design and cost estimates
- operational flexibility
- sensitivity of the technology to fire, flood, drought and hurricanes
- level of effort required to manage, and the potential benefits to be derived from, side streams generated by the treatment process
- other water quality issues

Where appropriate, we have incorporated findings from assessments and observations into this document to substantiate the “qualitative” concepts.

As part of the STSOC, the phosphorus removal model used for footprint ‘sizing’ must be calibrated using data sets from one or more time periods. Guidelines for modeling, and selection of appropriate platforms and calibration periods, were suggested by Kadlec (2001) as follows:

1) “The model results for a given data set should correspond to observations”
2) “The calibration data set should extend well past the dominance of initial conditions”
3) “Sufficient calibration power should be allocated to permanent removal as opposed to grow-in”
4) “The period should encompass at least one full suite of seasons”
5) “The scale of experimental system should be appropriate”
6) “Forecasts should be limited to the calibration envelope”
7) “Construction, operation and management requirements, associated with the evaluation platform, should be feasible at the intended scale of operation”

With the above guidelines in mind, for purposes of Post-BMP analysis we selected north test cell 15 (NTC-15), with July 2000 – September 2001 as the calibration period (440 days) and August 17 – 31, 2001 as the STSOC “verification” period. For Post-STA analysis, we selected Cell 4 of STA-1W, because of its large size (147 ha) and long operational history (September 1993 – present). The Cell 4 model calibration period was January 1, 1998 through September 30, 2001. The verification period for this wetland (not included in model calibration, but used for intensive sampling) was December 7 – 31, 2001.

# Section 2: Description of Data Collection and Synthesis Methods

Findings in this document result primarily from monitoring and assessments performed in the 0.2 ha test cells (NTC-15 and STC-9), as well as in the 147 ha Cell 4. Selected data also were obtained from several other platforms, including outdoor microcosms, mesocosms and the 930 ha Cell 5B of (STA)-1W.

## 2.1 STSOC Verification Sampling

The purpose of STCOC verification sampling was to intensively monitor performance of an SAV/LR wetland under “optimum” conditions, for a period of five hydraulic retention times. We performed STSOC verification sampling using three platforms: Post-BMP waters into North Test Cell 15 (NTC 15) (Figure 2-1); Post-STA waters (from inflow region of STA-1W Cell 3) into South Test Cell 9 (STC 9); and Post-STA waters (outflow from STA-1W Cell 2) into STA-1W Cell 4, (Figure 2-2). At the start of the Phase II effort, we equipped NTC 15 and STC 9 with limerock berms, located approximately 90% down the length of the cells. Verification sampling periods for these platforms were as follows:

- North Test Cell 15, Aug. 17 to Aug. 31, 2001
- South Test Cell 9, Aug. 17 to Sept. 28, 2001
- Cell 4, Dec. 7 to Dec. 31, 2001

**Figure 2-1.** North Test Cell 15, following installation of limerock berm. View is from outflow to inflow of the cell. The SAV region in the foreground of the berm comprises 10% of the wetland area.

**Figure 2-2.** Aerial photo of Cell 4. View is from the outflow towards the inflow levee.

## 2.2 Sample Locations

At the test cells, hourly composited water quality samples were collected at the head cell (inflow), pre-limerock berm, and test cell effluent (weir outflow). Grab samples were collected from the PVC influent manifold to each individual cell. The pre-limerock berm station consisted of a composite of grab samples from three sample points equidistant along the berm. The test cell effluent samples were collected at the weir outflow stations.

The inflow levee into Cell 4 originally consisted of five 72” culverts, but four more were added in 1999. The outflow station is comprised of five 72” culverts. Cell 4 influent grab and composite samples were collected at culverts G-254D and G-254G, and then composited into a single sample. Effluent grab and composite samples were collected from culvert G-256B. A duplicate was collected from culvert G-256D.

## 2.3 Flow Measurements

Test cell inflow rates are controlled principally by an orifice plate on the main feed pipe. The feed pipe conveys water from a “head cell”, whose level fluctuates slightly during the day. Inflows into the test cells were measured manually (“bucket and stopwatch” method at each inflow manifold port) and recorded three times per week.

Test cell outflows were not directly measured. For purposes of mass removal calculations, outflows were assumed to equal inflows. This provides a conservative measure of mass removal, since the outflows were likely slightly less than the inflows due to the influence of evaporation. The influence of rainfall events on outflows was not quantified, since in the test cells the response time of the outflows to rainfall events typically is rapid, and of short duration.

Cell 4 inflows and outflows are monitored remotely by District personnel, using ultrasonic velocity meters (UVMs) situated in each culvert. Our previous assessments of Cell 4 inflows and outflows suggest seepage losses from the wetland are in the range of 10%.

## 2.4 Water Quality Parameters, Sampling Methods

Composite samples were collected three times per week during the verification period (approximately 5 hydraulic retention times for each platform) using automated ISCO samplers. Samples that required preservation were either pre-preserved or preserved immediately after collection. Aliquots for total soluble P (TSP), SRP and dissolved metals were filtered in the field with a 0.45 µm filter. Samples were collected into containers that were previously cleaned and labeled. After collection and processing, samples were immediately placed on ice in coolers, and either sent immediately to the designated laboratory for next day analysis (grab samples) or stored in an on-site refrigerator for subsequent analysis within the prescribed holding time. Grab samples were used for selected analytes due to limited holding times. Frequencies and parameters for the samples collected are provided in Table 2-1.

Physical parameters were recorded at the time of water sampling. Sampling was performed according to methods outlined in DBE's FDEP approved Quality Assurance Project Plan (QAPP) approved by the SFWMD. All P associated parameters, alkalinity, color, turbidity, and conductivity samples were analyzed by DBE per Comprehensive Quality Assurance Project Plan (CompQAP) No. 910048. PPB Environmental Laboratory analyzed dissolved Fe (CompQAP No. 870017). All remaining parameters were analyzed by Sanders Laboratory (CompQAP No. 930013).

## 2.5 Quality Assurance Protocols

All sampling procedures, including field sample collection protocols, preservation and chain of custody forms, were performed according to the QAPP prepared by DBE. Calibration of field equipment according to the manufacturer's equipment guidelines was completed in the field and recorded in data notebooks by field technicians. After each sample collection, a dilute bleach solution was passed through all autosampler tubing, to prevent algal growth. Tubing subsequently was rinsed with deionized water. Sample composite jars were washed with soap and 10% HCl and then rinsed with deionized water. Analysis of samples and validation of data was performed by laboratory personnel according to each laboratory's CompQAP. Field duplicates were collected at the rate of 10% of total samples and equipment blanks were collected at a rate of 5% total samples in accordance with DBE's QAPP.

**Table 2-1.** Methods and frequency for samples collected during the verification period.

| Parameters | Units | Analytical Method | Method Detection Limit | Sampling Frequency |
|---|---|---|---|---|
| TP | mg/L as P | EPA 365.2 | 0.004 | 24 hr composite, 3 times per week |
| TSP | mg/L as P | EPA 365.2 | 0.004 | Grab twice per week |
| SRP | mg/L as P | EPA 365.2 | 0.002 | Grab twice per week |
| Turbidity | NTU | EPA 180.1 | 0.02 | Grab twice per week |
| Color | CPU | EPA 110.2 | 8 | Grab twice per week |
| TSS | mg/L | EPA 160.2 | 0.7 | Every 3rd composite |
| TOC | mg/L | EPA 415.1 | 1 | Every 3rd composite |
| Alkalinity | mg/L as | EPA 310.1 | 1 | Every 3rd composite |
| TDS | $CaCO_3$ | EPA 160.1 | 7 | Every 3rd composite |
| TKN | mg/L | EPA 351.2 | 0.0001 | Every 3rd composite |
| Nitrate + Nitrite | mg/L as N | EPA 300.0 | 2 | Every 3rd composite |
| Ammonia | µg/L as N<br>mg/L as N | EPA 350.3 | 0.002 | Every 3rd composite |
| Sulfate | mg/L | EPA 300.0 | 1.5 | Composite five times |
| Chloride | mg/L | EPA 300.0 | 0.02 | Composite five times |
| Dissolved Al | µg/L | EPA 200.7 | 28 | Composite five times |
| Dissolved Fe | µg/L | EPA 200.7 | 4 | Composite five times |
| Dissolved Ca | mg/L | EPA 200.7 | 0.0013 | Composite five times |
| Dissolved Mg | mg/L | EPA 200.7 | 0.004 | Composite five times |
| Dissolved K | mg/L | EPA 200.7 | 0.034 | Composite five times |
| Dissolved Na | mg/L | EPA 273.1 | 0.003 | Composite five times |
| Reactive Silica | mg/L | EPA 370.1 | 0.02 | Composite five times |
| Conductivity[1] | µs/cm | EPA 120.1 | 0.3 | Twice per week |
| DO[2] | mg/L | EPA 360.1 | 0.1 | Twice per week |
| pH | (PR) | EPA 150.1 | 0.1 | Twice per week |
| Temperature | (PR) | EPA 110.2 | 1 | Twice per week |

[1] Conductivity was collected as a grab sample and analyzed at DBE.
[2] DO was measured in-situ; pH and temperature measurements were performed on the grab sample.

# Section 3: Summary of SAV/LR Performance

This section provides a performance synopsis of SAV/LR systems for the STSOC verification period, and where applicable, the model calibration periods and entire period of operation. The platforms addressed are NTC-15, STC-9 and Cell 4. Performance is described with respect to minimum achievable outflow TP concentrations, TP mass removal efficiencies and other general water quality parameters.

## 3.1 Routine SAV/LR Monitoring

Routine monitoring results for the three STSOC platforms (NTC-15, STC-9 and Cell 4) are provided in the following sections.

### 3.1.1 Phosphorus Removal During Period of Record

*North Test Cell 15 and South Test Cell 9*

North Test Cell 15 (NTC-15) and South Test Cell 9 (STC-9) were subject to varying water depths, HLRs and a long-term drawdown for berm construction early in 2000. While the water depths were low, we also applied some granular herbicides to kill small patches of hydrilla that had invaded the test cells. The submerged macrophytes (principally *Chara* in both cells) suffered from dessication and some herbicide burning during the drawdown. We therefore selected a period two months for NTC-15 and four months for STC-9 after completion of berm construction to initiate the "calibration" period for these test cells. We also use this as the start of our reporting period of record.

*Cell 4*

Cell 4 was initially flooded in September 1993, and flow-through operations were initiated on August 18, 1994. Deployment of culvert flow instrumentation was completed in early 1995. Period of record inflow and outflow TP concentrations for Cell 4, beginning from the date of first outflow, are provided in Figure 3-1. Mean (arithmetic average) TP inflow and outflow concentrations for the wetland from 2/1/95 until 9/30/01 were 52 and 22 µg/L, respectively. Mass P removal by Cell 4 during the period of record averaged 1.6 gP/m$^2$-yr, with a mean TP removal rate of 62%. Note that P removal performance during the first two operational years was poor, but the wetland has consistently provided a net removal of P since that time.

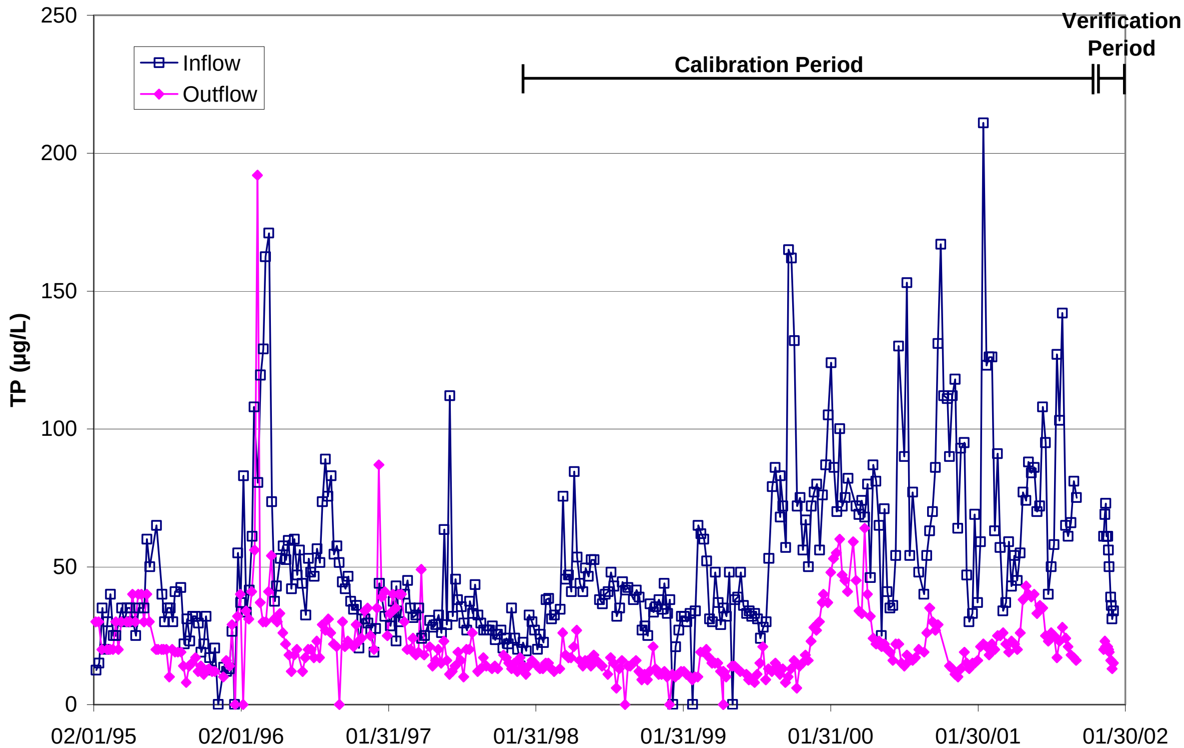



**Figure 3-1.** Inflow and outflow TP concentrations for STA-1W Cell 4.

### 3.1.2 Phosphorus Removal During Calibration Period

*North Test Cell 15*

During the calibration period (July 1, 2000 – September 14, 2001), NTC-15 was subjected to a gradually increasing flow regime. From July 2000 – March 2001, inflows averaged 140 $m^3$/day (5.1 cm/day). From March – May 2001, inflows averaged 320 $m^3$/day (11.7 cm/day), and from June – Sept. 2001, mean inflows were 588 $m^3$/day (21.5 cm/day). Water depths primarily were 0.96 m for the first portion of the assessment (until April 2001), and 0.6 m for the second portion of the monitoring period. These corresponded to hydraulic retention times of 12.9 and 3.5 days, respectively.

Mean inflow and outflow constituent concentrations for NTC-15 during the calibration period are provided in Table 3-1. Data are shown for the inflow station, the pre-berm station, representing the performance of the SAV community in the first 87% of the wetland, and finally

**Table 3-1.** NTC-15 and STC-9 inflow and outflow constituent concentrations during the calibration period (NTC-15: July 1, 2000 – September 14, 2001, STC-9: July 31, 2000 – September 14, 2001). Pre-berm samples were collected from the upstream side of the limerock berm. Outflow samples were collected from the cell effluent weir.

| Parameter | Units | ID | NTC-15 | | | | | | STC-9 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Avg. | Stdev | Median | Max | Min | n | Avg. | Stdev | Median | Max | Min | n |
| **TP** | **µg/L** | Inflow | 71 | 32 | 62 | 151 | 25 | 63 | 26 | 9 | 23 | 46 | 13 | 59 |
| | | Pre-Berm | 23 | 8 | 22 | 43 | 10 | 63 | 21 | 11 | 19 | 90 | 11 | 59 |
| | | Outflow | 20 | 6 | 21 | 35 | 7 | 63 | 17 | 4 | 17 | 32 | 10 | 59 |
| **TSP** | **µg/L** | Inflow | 40 | 26 | 28 | 108 | 12 | 63 | 16 | 7 | 14 | 57 | 9 | 59 |
| | | Pre-Berm | 11 | 3 | 11 | 19 | 5 | 63 | 10 | 2 | 10 | 17 | 5 | 59 |
| | | Outflow | 10 | 3 | 10 | 17 | 4 | 63 | 10 | 2 | 10 | 19 | 6 | 59 |
| **SRP** | **µg/L** | Inflow | 25 | 21 | 17 | 93 | 2 | 62 | 6 | 4.1 | 5 | 30 | <2.0 | 58 |
| | | Pre-Berm | 2 | 1.2 | 2 | 7 | <2.0 | 62 | 2 | 0.7 | 2 | 4 | <2.0 | 58 |
| | | Outflow | 2 | 1.2 | 2 | 9 | <2.0 | 62 | 2 | 1.2 | 2 | 7 | <2.0 | 58 |
| **DOP** | **µg/L** | Inflow | 15 | 13 | 13 | 104 | 6 | 63 | 10 | 3.5 | 10 | 27 | 3 | 58 |
| | | Pre-Berm | 9 | 3.4 | 9 | 16 | 2 | 63 | 8 | 2.3 | 8 | 15 | 4 | 58 |
| | | Outflow | 8 | 2.8 | 8 | 16 | <2.0 | 62 | 8 | 2.9 | 8 | 18 | 2 | 59 |
| **PP** | **µg/L** | Inflow | 30 | 12 | 29 | 73 | 8 | 63 | 10 | 8 | 7 | 31 | <2.0 | 59 |
| | | Pre-Berm | 12 | 5 | 12 | 27 | 3 | 63 | 12 | 9 | 10 | 73 | 3 | 59 |
| | | Outflow | 10 | 4 | 10 | 22 | <2.0 | 62 | 7 | 4 | 7 | 18 | <2.0 | 59 |
| **Alk.** | **mg/L** | Inflow | 297 | 23 | 302 | 332 | 234 | 62 | 273 | 20 | 276 | 306 | 232 | 58 |
| | | Pre-Berm | 223 | 53 | 241 | 298 | 118 | 62 | 186 | 55 | 182 | 274 | 82 | 58 |
| | | Outflow | 233 | 34 | 241 | 298 | 118 | 62 | 200 | 43 | 201 | 298 | 126 | 58 |
| **Spec. Cond.** | **µs/cm** | Inflow | 1219 | 111 | 1228 | 1457 | 945 | 61 | 1179 | 131 | 1202 | 1459 | 911 | 57 |
| | | Pre-Berm | 1071 | 152 | 1077 | 1309 | 725 | 61 | 1015 | 208 | 1011 | 1748 | 700 | 57 |
| | | Outflow | 1096 | 131 | 1077 | 1309 | 725 | 61 | 1036 | 170 | 1228 | 1457 | 945 | 56 |

| Parameter | Units | ID | NTC-15 | | | | | | STC-9 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Avg. | Stdev | Median | Max | Min | n | Avg. | Stdev | Median | Max | Min | n |
| **Ca** | **mg/L** | Inflow | 82 | 9 | 83 | 106 | 30 | 61 | 71 | 10 | 73 | 89 | 27 | 56 |
| | | Pre-Berm | 55 | 19 | 58 | 88 | 16 | 61 | 34 | 12 | 31 | 57 | 16 | 56 |
| | | Outflow | 56 | 14 | 55 | 84 | 16 | 61 | 38 | 9 | 36 | 61 | 14 | 55 |
| **TKN** | **mg/L** | Inflow | 2.6 | 1.1 | 2.9 | 3.6 | 0.4 | 7 | 3.7 | 3.0 | 2.4 | 10.4 | 2.1 | 7 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 2.5 | 0.5 | 2.4 | 3.5 | 2.1 | 7 | 2.3 | 0.5 | 2.5 | 2.7 | 1.2 | 7 |
| **$NO_3$+$NO_2$** | **mg/L** | Inflow | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 7 | <0.05 | 0 | < 0.05 | < 0.05 | <0.05 | 7 |
| | | Pre-Berm | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 7 | <0.05 | 0 | < 0.05 | < 0.05 | <0.05 | 7 |
| | | Outflow | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 7 | <0.05 | 0 | < 0.05 | < 0.05 | <0.05 | 7 |
| **$NH_4$** | **mg/L** | Inflow | 0.31 | 0.17 | 0.34 | 0.49 | 0.03 | 7 | 0.15 | 0.13 | 0.09 | 0.44 | 0.06 | 7 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 0.13 | 0.06 | 0.14 | 0.21 | 0.06 | 7 | 0.08 | 0.26 | 0.08 | 0.73 | 0.03 | 7 |
| **TSS** | **mg/L** | Inflow | 1.1 | 0.9 | 1.0 | 2.2 | 0.3 | 6 | 0.5 | 0.5 | 0.3 | 1.4 | 0.1 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 0.8 | 0.6 | 0.6 | 1.6 | 0.3 | 6 | 2.6 | 4.2 | 1.0 | 11 | 0.3 | 6 |
| **pH** | **units** | Inflow | 7.43 | 0.2 | 7.41 | 8.11 | 6.81 | 207 | 7.62 | 0.3 | 7.65 | 9.81 | 6.89 | 190 |
| | | Pre-Berm | 8.36 | 0.6 | 8.21 | 9.89 | 7.46 | 207 | 8.97 | 0.6 | 8.95 | 10.34 | 7.77 | 191 |
| | | Outflow | 7.72 | 0.2 | 7.70 | 9.21 | 7.28 | 207 | 8.37 | 0.3 | 8.35 | 9.17 | 7.63 | 191 |
| **Temp** | **˚C** | Inflow | 25.1 | 4.1 | 25.9 | 32.8 | 7.2 | 205 | 25.5 | 4.2 | 26.3 | 34.9 | 7.8 | 188 |
| | | Pre-Berm | 27.3 | 4.1 | 28.0 | 35.9 | 11.8 | 205 | 26.5 | 4.8 | 27.3 | 35.3 | 7.8 | 189 |
| | | Outflow | 25.2 | 4.3 | 26.8 | 33.8 | 7.8 | 205 | 25.1 | 3.8 | 26.0 | 31.2 | 11.6 | 189 |

the outflow station, which represents the additional P removal provided by the limerock berm and “back end” polishing wetland.

The P removal performance of the SAV community alone is best described by comparing inflow and pre-berm P concentrations (Figure 3-2). Mean TP inflow and outflow (pre-berm) concentrations for the calibration period were 73 and 23 µg/L, respectively. The SAV community removed essentially all of the SRP from the Post-BMP waters, reducing levels of this constituent from 25 to 2 µg/L. The SAV community also provided some reduction of PP (from 31 to 11 µg/L) and DOP (from 16 to 9 µg/L) during the calibration period. Mass P removal during the calibration period averaged 2.1 gP/m$^2$-yr and the percentage of P removed by the SAV wetland was 64%.

The TP performance of the limerock berm (and downstream wetland) initially was poor, but improved with time during the calibration period (Figure 1-11).

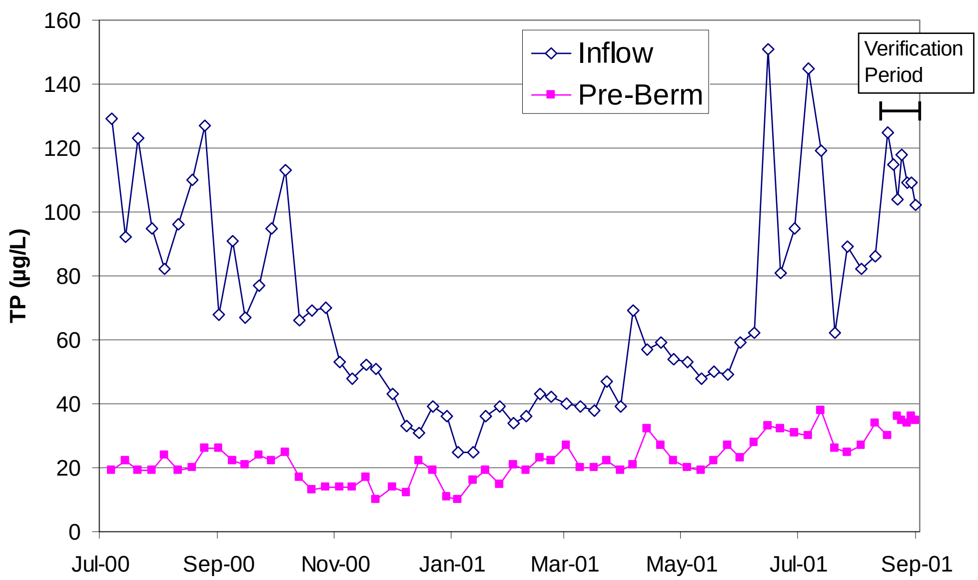



**Figure 3-2**. Calibration period and STSOC verification period inflow and outflow (pre-berm) TP concentrations for NTC-15.

*South Test Cell 9*

During the calibration period (July 31, 2000 – September 14, 2001) for STC-9, flows and water depths were subject to less variation than for NTC-15. The test cell inflows were consistent, at 149 $m^3$/day (5.4 cm/day) during the entire period. With the exception of a three week period in May where the water depth was 0.3m, the test cell water depth was maintained between 0.45 and 0.55 m.

Mean inflow and outflow constituent concentrations for STC-9 during the calibration period are provided in Table 3-1. Data are shown for the inflow station, the pre-berm station, and the test cell outflow location. Mean test cell TP inflow and outflow (pre-berm) concentrations for the calibration period were 28 and 21 µg/L, respectively (Figure 3-3). The low concentrations of SRP in the inflow waters (6 µg/L) were stripped to background levels (2 µg/L) with passage through the test cell. On average, we observed no net removal of PP by the SAV community, and DOP concentrations were only slightly reduced, from 10 to 8 µg/L. Mass P removal during the calibration period averaged 0.13 gP/$m^2$-yr and the percentage of P removed by the SAV wetland was 15%.

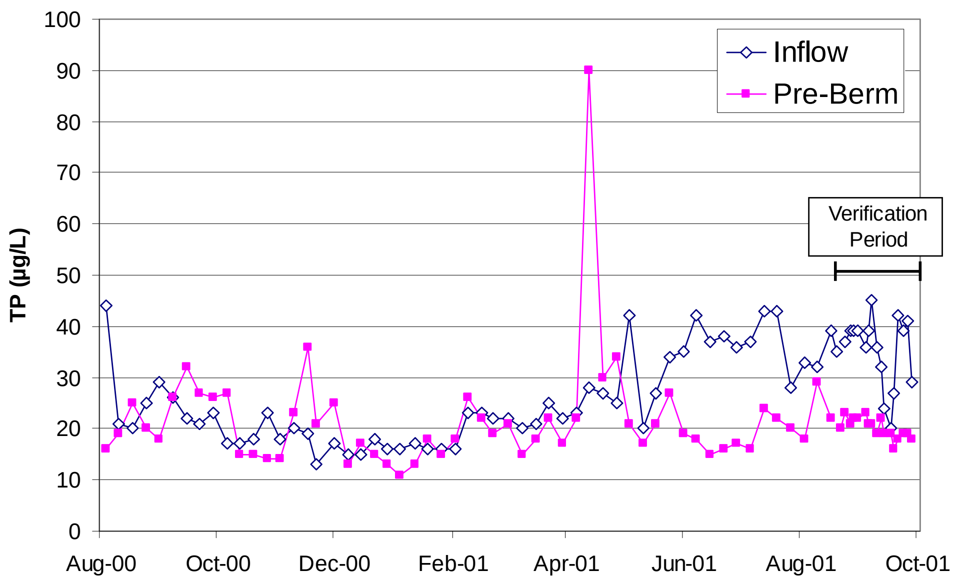



**Figure 3-3.** Calibration period and STSOC verification period inflow and outflow (pre-berm) TP concentrations for STC-9.

*Cell 4*

Cell 4 inflow and outflow TP concentrations during the calibration period averaged 61 and 20 μg/L, respectively. The Cell 4 inflow and outflow TP concentrations during the calibration period are shown in Figure 3-1. The mass removal rate during this time was 1.86 gP/$m^2$-yr, and the wetland removed 73% of the inflow P loading.

## 3.2 STSOC Verification Performance Period Results

### 3.2.1 Phosphorus Results

*NTC – 15*

During the two week NTC-15 verification period, the TP concentrations of the test cell inflow waters were high, averaging 112 µg/L (Table 3-2). Outflow (pre-berm) concentrations from the SAV wetland averaged 34 µg/L (Figure 3-4). The SAV wetland effectively removed all of the labile P, reducing SRP concentrations from 63 to 3 µg/L. Dissolved organic P concentrations were reduced from 20 to 13 µg/L, and PP concentrations were reduced from 31 to 18 µg/L. The test cell removed 69% of the TP during the verification period, and provided a mass removal rate of 6.5 gP/$m^2$-yr.

The limerock berm (and downstream wetland) provided effective P removal during the verification period, reducing pre-berm TP concentrations of 34 µg/L to 25 µg/L at the cell outflow (Figure 3-5).

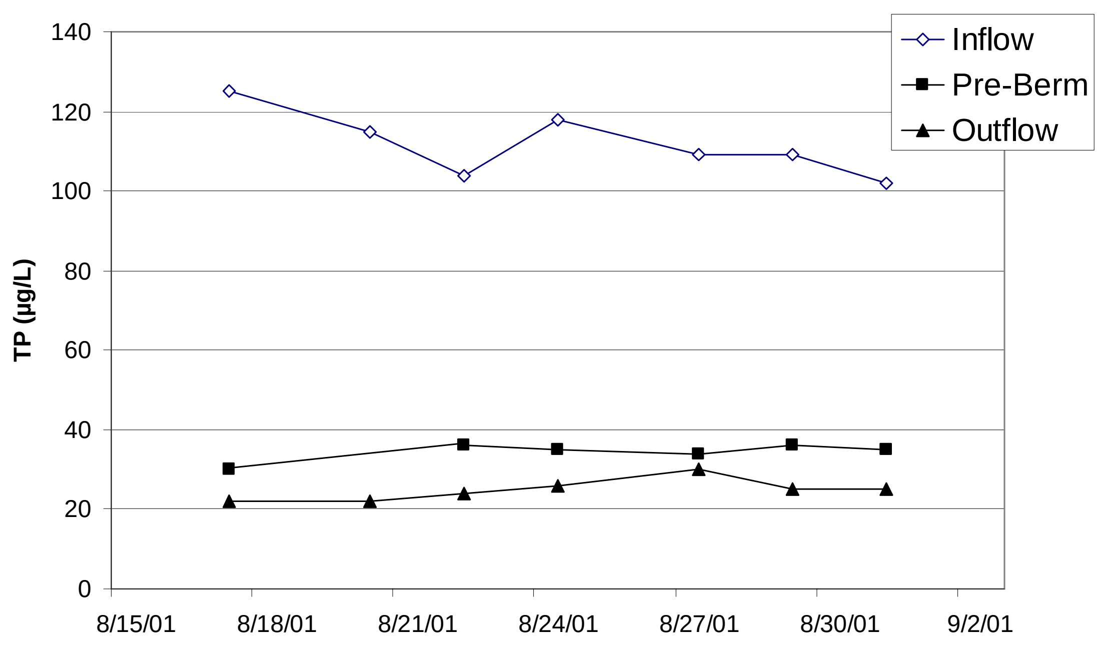



**Figure 3-4.** TP removal performance of the NTC-15 SAV/LR test cell during the STSOC verification period.

**Table 3-2.** NTC-15 and STC-9 inflow and outflow constituent concentrations from during the STSOC verification period. Pre-berm samples were collected from the upstream side of the limerock berm. Outflow samples were collected from the cell effluent weir**.**

| Parameter | Units | ID | NTC-15 (8/17/01 – 8/31/01) | | | | | | STC-9 (8/17/01 – 9/29/01) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Avg | Stdev | Median | Max | Min | n | Avg | Stdev | Median | Max | Min | n |
| **TP** | **µg/L** | Inflow | 112 | 8 | 109 | 125 | 102 | 7 | 35 | 7 | 38 | 45 | 20 | 18 |
| | | Pre-Berm | 34 | 2 | 35 | 36 | 30 | 6 | 20 | 2 | 20 | 23 | 16 | 18 |
| | | Outflow | 25 | 3 | 25 | 30 | 22 | 7 | 19 | 2 | 19 | 22 | 55 | 19 |
| **TSP** | **µg/L** | Inflow | 82 | 17 | 75 | 111 | 68 | 5 | 14 | 2 | 13 | 18 | 11 | 13 |
| | | Pre-Berm | 16 | 2 | 17 | 18 | 14 | 5 | 10 | 1 | 10 | 13 | 8 | 13 |
| | | Outflow | 13 | 1 | 13 | 14 | 12 | 5 | 10 | 2 | 10 | 14 | 8 | 13 |
| **SRP** | **µg/L** | Inflow | 63 | 15 | 61 | 87 | 48 | 5 | 2l | 1.7 | 3 | 6 | < 2.0 | 13 |
| | | Pre-Berm | 3 | 1.1 | 4 | 2 | 4 | 5 | 2 | 1.1 | 2 | 4 | < 2.0 | 13 |
| | | Outflow | 3 | 1.1 | 2 | 4 | 2 | 5 | 2 | 1.1 | 2 | 5 | < 2.0 | 13 |
| **DOP** | **µg/L** | Inflow | 20 | 4.1 | 20 | 24 | 13 | 5 | 11 | 2.0 | 11 | 14 | 8 | 13 |
| | | Pre-Berm | 13 | 2.3 | 14 | 15 | 10 | 5 | 8 | 1.4 | 8 | 11 | 6 | 13 |
| | | Outflow | 10 | 1.5 | 11 | 12 | 8 | 5 | 8 | 2.1 | 8 | 12 | 4 | 13 |
| **PP** | **µg/L** | Inflow | 31 | 13 | 32 | 36 | 14 | 5 | 21 | 6 | 23 | 28 | 7 | 12 |
| | | Pre-Berm | 18 | 14 | 19 | 21 | 13 | 4 | 11 | 2 | 11 | 14 | 6 | 12 |
| | | Outflow | 11 | 3.1 | 12 | 16 | 8 | 5 | 8 | 2 | 8 | 11 | 6 | 13 |
| **Alk.** | **mg $CaCO_3$/ L** | Inflow | 284 | 0 | 284 | 284 | 284 | 2 | 274 | 8 | 272 | 284 | 266 | 5 |
| | | Pre-Berm | 251 | 1 | 251 | 252 | 250 | 2 | 200 | 22 | 203 | 224 | 168 | 5 |
| | | Outflow | 242 | 3 | 242 | 244 | 240 | 2 | 202 | 16 | 206 | 217 | 171 | 5 |
| **Turb.** | **NTU** | Inflow | 2.0 | 1.4 | 2.0 | 3.3 | 0.7 | 4 | 1.2 | 0.8 | 1.0 | 3.6 | 0.4 | 12 |
| | | Pre-Berm | 1.4 | 0.5 | 1.3 | 2.0 | 0.9 | 4 | 1.9 | 1.1 | 1.4 | 4.6 | 0.9 | 12 |
| | | Outflow | 0.9 | 0.2 | 0.9 | 1.0 | 0.7 | 4 | 1.4 | 0.5 | 1.6 | 2.5 | 0.6 | 12 |
| **Spec. Cond.** | **µs/cm** | Inflow | 1031 | 66 | 1019 | 1111 | 954 | 5 | 1014 | 50 | 1013 | 1083 | 913 | 13 |
| | | Pre-Berm | 987 | 42 | 979 | 1038 | 929 | 5 | 872 | 65 | 858 | 988 | 779 | 13 |
| | | Outflow | 1000 | 55 | 992 | 1076 | 933 | 5 | 864 | 63 | 849 | 982 | 778 | 13 |
| **Color** | **CPU** | Inflow | 389 | 31 | 373 | 435 | 361 | 5 | 329 | 21 | 331 | 355 | 285 | 13 |
| | | Pre-Berm | 355 | 12 | 354 | 369 | 340 | 5 | 262 | 22 | 258 | 302 | 236 | 12 |
| | | Outflow | 347 | 9 | 351 | 353 | 333 | 5 | 247 | 14 | 246 | 268 | 221 | 13 |
| **Ca** | **mg/L** | Inflow | 98 | 2 | 98 | 101 | 95 | 6 | 91 | 8 | 91 | 104 | 83 | 6 |
| | | Pre-Berm | 82 | 2 | 82 | 86 | 79 | 5 | 50 | 5 | 50 | 55 | 43 | 5 |
| | | Outflow | 84 | 2 | 84 | 86 | 80 | 6 | 50 | 4 | 50 | 57 | 44 | 6 |
| **Fe** | **mg/L** | Inflow | 54 | 14 | 50 | 76 | 40 | 6 | 14 | 5.6 | 14 | 20 | 5.8 | 6 |
| | | Pre-Berm | 31 | 7 | 29 | 43 | 24 | 5 | 2.5 | 0.7 | 2.5 | 2.5 | 1.3 | 5 |
| | | Outflow | 38 | 9 | 34 | 54 | 30 | 6 | 5.1 | 5.6 | 3.7 | 16 | 1.3 | 6 |
| **Al** | **mg/L** | Inflow | <0.02 | 0 | < 0.02 | <0.02 | <0.02 | 6 | <0.02 | 0 | < 0.02 | <0.02 | <0.02 | 6 |
| | | Pre-Berm | <0.02 | 0 | <0.02 | <0.02 | <0.02 | 5 | <0.02 | 0 | <0.02 | <0.02 | <0.02 | 5 |
| | | Outflow | <0.02 | 0 | <0.02 | <0.02 | <0.02 | 6 | <0.02 | 0 | <0.02 | <0.02 | <0.02 | 6 |

| Parameter | Units | ID | NTC-15 (8/17/01 – 8/31/01) | | | | | | STC-9 (8/17/01 – 9/29/01) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Avg | Stdev | Median | Max | Min | n | Avg | Stdev | Median | Max | Min | n |
| **K** | **mg/L** | Inflow | 8.4 | 0.4 | 8.5 | 8.8 | 7.9 | 6 | 9.8 | 0.5 | 9.7 | 10.7 | 9.2 | 6 |
| | | Pre-Berm | 8.4 | 0.4 | 8.4 | 8.8 | 7.8 | 5 | 9.7 | 0.8 | 9.4 | 10.7 | 9.0 | 5 |
| | | Outflow | 8.5 | 0.5 | 8.4 | 9.1 | 7.8 | 6 | 9.9 | 0.7 | 10 | 10.7 | 9.0 | 6 |
| **Na** | **mg/L** | Inflow | 102 | 12 | 101 | 118 | 85 | 6 | 104 | 8 | 101 | 119 | 96 | 6 |
| | | Pre-Berm | 101 | 13 | 102 | 117 | 88 | 5 | 106 | 9 | 107 | 117 | 94 | 5 |
| | | Outflow | 101 | 13 | 100 | 118 | 87 | 6 | 106 | 8 | 108 | 114 | 93 | 6 |
| **Si** | **mg/L** | Inflow | 6 | 10 | 0.3 | 25 | 0.05 | 6 | 14 | 13 | 14 | 30 | 0.1 | 6 |
| | | Pre-Berm | 5 | 11 | 0.3 | 25 | 0.05 | 5 | 15 | 19 | 5.0 | 38 | 0.2 | 5 |
| | | Outflow | 8 | 12 | 0.3 | 25 | 0.20 | 6 | 20 | 16 | 27 | 34 | 0.1 | 6 |
| **SO4** | **mg/L** | Inflow | 73 | 2 | 73 | 76 | 71 | 6 | 64 | 8 | 65 | 72 | 50 | 6 |
| | | Pre-Berm | 69 | 2 | 69 | 72 | 66 | 5 | 47 | 8 | 45 | 59 | 37 | 5 |
| | | Outflow | 69 | 2 | 69 | 71 | 66 | 6 | 50 | 7 | 48 | 59 | 43 | 6 |
| **Cl** | **mg/L** | Inflow | 125 | 10 | 122 | 144 | 112 | 6 | 128 | 11 | 127 | 140 | 113 | 6 |
| | | Pre-Berm | 123 | 11 | 121 | 135 | 114 | 5 | 134 | 7 | 135 | 141 | 125 | 5 |
| | | Outflow | 122 | 11 | 118 | 140 | 113 | 6 | 129 | 11 | 122 | 144 | 112 | 6 |
| **TSS** | **mg/L** | Inflow | 1.8 | 0.6 | 1.8 | 2.2 | 1.3 | 2 | 0.9 | 0.4 | 1.1 | 1.4 | 0.3 | 5 |
| | | Pre-Berm | 1.3 | 0.6 | 1.3 | 1.7 | 0.9 | 2 | 1.3 | 0.5 | 1.3 | 2.3 | 0.8 | 6 |
| | | Outflow | 0.7 | 0.4 | 0.7 | 1.0 | 0.4 | 2 | 0.7 | 0.4 | 0.7 | 1.2 | <0.06 | 6 |
| **TDS** | **mg/L** | Inflow | 698 | 20 | 698 | 712 | 684 | 2 | 678 | 46 | 664 | 740 | 628 | 5 |
| | | Pre-Berm | 638 | 31 | 638 | 660 | 616 | 2 | 582 | 39 | 580 | 644 | 540 | 5 |
| | | Outflow | 656 | 11 | 656 | 664 | 648 | 2 | 564 | 46 | 573 | 608 | 480 | 6 |
| **TKN** | **mg/L** | Inflow | 2.8 | 0.3 | 2.8 | 3.0 | 2.6 | 2 | 2.5 | 0.2 | 2.6 | 2.7 | 2.2 | 5 |
| | | Pre-Berm | 2.7 | 0.5 | 2.7 | 3.0 | 2.3 | 2 | 2.4 | 0.3 | 2.2 | 2.8 | 2.1 | 6 |
| | | Outflow | 2.6 | 0.2 | 2.6 | 2.8 | 2.4 | 2 | 2.2 | 0.2 | 2.2 | 2.6 | 2.0 | 6 |
| **$NO_3$+$NO_2$** | **mg/L** | Inflow | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 2 | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 5 |
| | | Pre-Berm | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 2 | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 6 |
| | | Outflow | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 2 | <0.05 | 0 | < 0.05 | <0.05 | <0.05 | 6 |
| **$NH_4$** | **mg/L** | Inflow | 0.36 | 0.10 | 0.36 | 0.43 | 0.29 | 2 | 0.20 | 0.08 | 0.23 | 0.31 | 0.10 | 5 |
| | | Pre-Berm | 0.13 | 0.01 | 0.13 | 0.13 | 0.12 | 3 | 0.14 | 0.06 | 0.12 | 0.22 | 0.08 | 6 |
| | | Outflow | 0.13 | 0.02 | 0.13 | 0.14 | 0.11 | 2 | 0.07 | 0.03 | 0.07 | 0.10 | 0.03 | 6 |
| **TOC** | **mg/L** | Inflow | 40 | 3 | 40 | 42 | 38 | 2 | 40 | 4 | 40 | 36 | 44 | 4 |
| | | Pre-Berm | 38 | -- | 38 | 38 | 38 | 1 | 33 | 13 | 36 | 42 | 7.9 | 6 |
| | | Outflow | 42 | 5 | 42 | 45 | 38 | 2 | 36 | 3 | 36 | 41 | 32 | 6 |
| **Hardness** | **mg/L** | Inflow | 339 | 8 | 340 | 346 | 330 | 3 | 299 | 7 | 299 | 309 | 288 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 318 | 9 | 320 | 325 | 309 | 3 | 220 | 11 | 215 | 237 | 211 | 6 |
| | | | | | | | | | | | | | | -- |
| **Total Mg** | **mg/L** | Inflow | 25 | 1.0 | 25 | 26 | 25 | 3 | 25 | 1 | 25 | 25 | 23 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 26 | 1.0 | 26 | 26 | 25 | 3 | 27 | 1 | 27 | 28 | 26 | 6 |
| **Total Ag** | **µg/L** | Inflow | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 3 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

| Parameter | Units | ID | NTC-15 (8/17/01 – 8/31/01) | | | | | | STC-9 (8/17/01 – 9/29/01) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Avg | Stdev | Median | Max | Min | n | Avg | Stdev | Median | Max | Min | n |
| | | Outflow | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 3 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 6 |
| **Total As** | **µg/L** | Inflow | 3.0 | 0.2 | 2.9 | 3.2 | 2.7 | 3 | 2.3 | 0.3 | 2.3 | 2.8 | 2.1 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 3.0 | 0.1 | 2.9 | 3.1 | 2.9 | 3 | 1.9 | 0.1 | 2.1 | 2.4 | 1.8 | 6 |
| **Total Cd** | **µg/L** | Inflow | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | 3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | 3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | 6 |
| **Total Cr** | **µg/L** | Inflow | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 3 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 3 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 6 |
| **Total Cu** | **µg/L** | Inflow | 1.8 | 0.1 | 1.8 | 1.9 | 1.7 | 3 | 1.6 | 0.2 | 1.7 | 1.8 | 1.5 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | 1.6 | 0.02 | 1.6 | 1.6 | 1.5 | 3 | 1.3 | 0.1 | 1.3 | 1.4 | 1.2 | 6 |
| **Total Ni** | **µg/L** | Inflow | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 3 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 3 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 6 |
| **Total Pb** | **µg/L** | Inflow | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 3 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 3 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 6 |
| **Total Se** | **µg/L** | Inflow | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | 3 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | 3 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | 6 |
| **Total Zn** | **µg/L** | Inflow | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 3 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 6 |
| | | Pre-Berm | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | | Outflow | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 3 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 6 |
| **pH** | **units** | Inflow | 7.22 | 0.12 | 7.27 | 7.34 | 7.07 | 6 | 7.47 | 0.30 | 7.46 | 7.95 | 7.06 | 6 |
| | | Pre-Berm | 7.99 | 0.12 | 7.94 | 8.21 | 7.90 | 6 | 8.56 | 0.28 | 8.57 | 8.92 | 8.13 | 6 |
| | | Outflow | 7.65 | 0.17 | 7.56 | 7.94 | 7.49 | 6 | 8.25 | 0.22 | 8.31 | 8.54 | 7.89 | 6 |
| **Temp** | **˚C** | Inflow | 29.9 | 1.0 | 29.8 | 31.0 | 28.7 | 6 | 29.3 | 1.4 | 29.7 | 30.7 | 27.6 | 6 |
| | | Pre-Berm | 31.7 | 2.2 | 31.8 | 34.6 | 28.3 | 6 | 30.1 | 1.0 | 29.9 | 31.7 | 29.0 | 6 |
| | | Outflow | 30.4 | 1.9 | 30.9 | 32.2 | 26.9 | 6 | 29.9 | 1.0 | 29.8 | 31.2 | 28.7 | 6 |
| **DO** | **mg/L** | Inflow | 0.4 | 0.4 | 0.2 | 1.0 | 0.1 | 5 | 0.2 | 0.2 | 0.1 | 0.6 | 0.0 | 5 |
| | | Pre-Berm | 14.8 | 2.1 | 14.5 | 18.2 | 12.5 | 5 | 5.1 | 4.2 | 7.5 | 8.8 | 0.4 | 5 |
| | | Outflow | 5.8 | 1.1 | 5.9 | 7.2 | 4.2 | 5 | 5.6 | 4.4 | 5.0 | 10.6 | 0.9 | 5 |

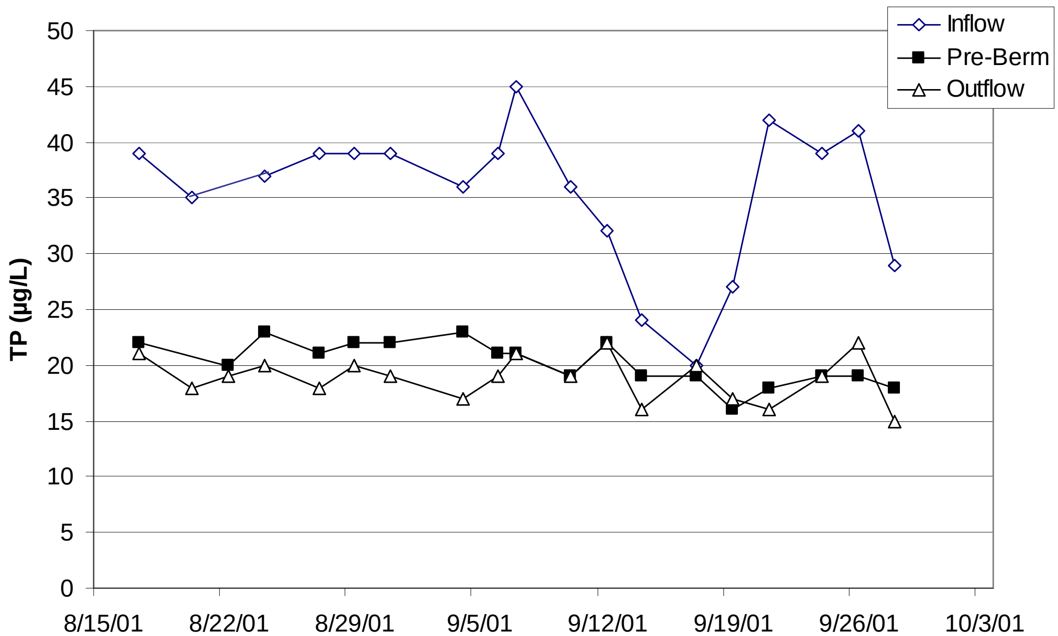



**Figure 3-5**. TP removal performance of the STC-9 SAV/LR test cell during the STSOC verification period.

*STC – 9*

During the six week verification period, test cell STC-9 reduced TP levels from an inflow of 35 to 20 µg/L at the pre-berm station (Table 3-2; Figure 3-4). The low inflow SRP concentrations (3 µg/L) were further reduced to 2 µg/L. Approximately 50% of the PP was removed during passage through the test cell (21 to 11 µg/L), but only minimal DOP removal was observed (11 to 8 µg/L). The test cell removed 41% of the TP during the verification period, and provided a mass removal rate of 0.32 gP/m$^2$-yr.

The limerock berm (and downstream wetland) provided little P removal during the verification period, reducing pre-berm TP concentrations of 20 µg/L to 19 µg/L (Figure 3-5).

*Cell 4*

Surface water inflows and outflows for Cell 4 during the verification period were almost identical, averaging 98 and 101 cfs, respectively. These flows are equivalent to a wetland HLR of 17 cm/day. These data suggest that little loss (seepage) or gain (rainfall) of water occurred in the wetland during the verification period. Cell 4 provided effective TP removal during the verification period, reducing mean inflow concentrations of 52 µg/L to 19 µg/L (Table 3-3; Figure 3-6). Approximately one half of the inflow TP was present as SRP (27 µg/L). SRP levels in the wetland outflow were substantially lower, at 6 µg/L. Cell 4 reduced DOP concentrations from 27 to 10 µg/L, and PP concentrations from 15 to 5 µg/L. Overall average TP removal was 62%, at a mass removal rate of 1.93 gP/m$^2$-yr.

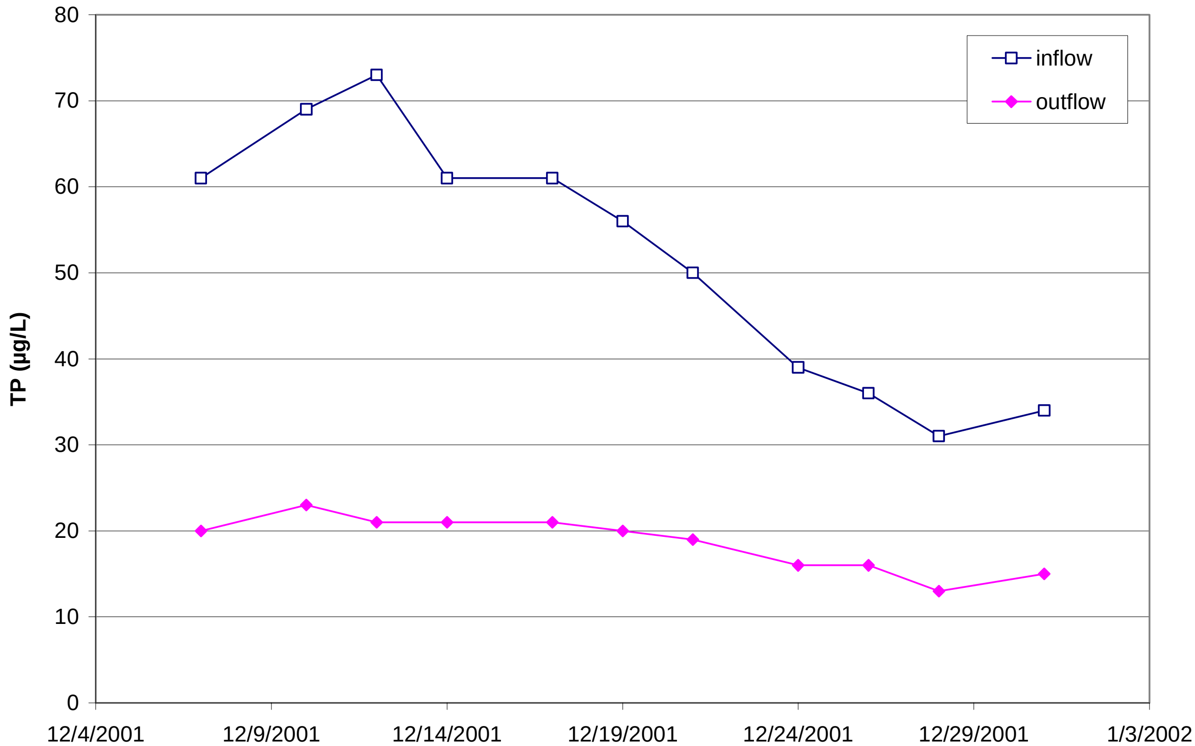



**Figure 3-6.** TP removal performance of Cell 4 during the STSOC verification period.

**Table 3-3.** Cell 4 inflow and outflow constituent concentrations during the STSOC verification period (12/7/01-12/31/01)

| Parameter | Units | ID | Cell 4 | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Avg | Std dev | Median | Max | Min | n |
| **TP** | **µg/L** | Inflow | 52 | 15 | 56 | 73 | 31 | 11 |
| | | Outflow | 19 | 3 | 20 | 23 | 13 | 11 |
| **TSP** | **µg/L** | Inflow | 54 | 34 | 46 | 134 | 25 | 8 |
| | | Outflow | 16 | 3 | 15 | 21 | 12 | 8 |
| **SRP** | **µg/L** | Inflow | 27 | 10 | 26 | 45 | 15 | 8 |
| | | Outflow | 6 | 2 | 5 | 8 | 4 | 8 |
| **DOP** | **µg/L** | Inflow | 27 | 37 | 16 | 117 | 5 | 8 |
| | | Outflow | 10 | 2 | 10 | 14 | 7 | 8 |
| **PP** | **µg/L** | Inflow | 15 | 10 | 15 | 31 | < 0.002 | 8 |
| | | Outflow | 5 | 2 | 5 | 7 | < 0.002 | 8 |
| **Alk.** | **mg $CaCO_3$/L** | Inflow | 183 | 28 | 170 | 216 | 164 | 3 |
| | | Outflow | 186 | 15 | 193 | 196 | 169 | 3 |
| **Turb.** | **NTU** | Inflow | 1.0 | 0.2 | 0.9 | 1.4 | 0.8 | 8 |
| | | Outflow | 0.9 | 0.2 | 1.0 | 1.2 | 0.6 | 8 |
| **Spec. Cond.** | **µs/cm** | Inflow | 681 | 95 | 630 | 819 | 597 | 8 |
| | | Outflow | 755 | 151 | 728 | 1020 | 610 | 8 |
| **Color** | **CPU** | Inflow | 240 | 20 | 240 | 273 | 215 | 8 |
| | | Outflow | 228 | 20 | 228 | 256 | 203 | 8 |
| **Ca** | **mg/L** | Inflow | 68 | 18 | 68 | 88 | 48 | 4 |
| | | Outflow | 68 | 14 | 68 | 84 | 52 | 4 |
| **Fe** | **µg/L** | Inflow | 14 | 2 | 14 | 16 | 13 | 4 |
| | | Outflow | 7 | 1 | 7 | 8 | 6 | 4 |
| **Al** | **mg/L** | Inflow | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 |
| | | Outflow | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 |
| **K** | **mg/L** | Inflow | 11 | 5 | 10 | 17 | 7 | 4 |
| | | Outflow | 14 | 5 | 13 | 19 | 9 | 4 |
| **Na** | **mg/L** | Inflow | 78 | 33 | 78 | 115 | 40 | 4 |
| | | Outflow | 92 | 34 | 93 | 129 | 51 | 4 |
| **Si** | **mg/L** | Inflow | 13 | 4 | 14 | 17 | 8 | 4 |
| | | Outflow | 13 | 2 | 14 | 14 | 9 | 4 |
| **$SO_4$** | **mg/L** | Inflow | 38 | 17 | 35 | 58 | 22 | 4 |
| | | Outflow | 47 | 24 | 48 | 72 | 17 | 4 |
| **Cl** | **mg/L** | Inflow | 92 | 16 | 90 | 110 | 77 | 4 |
| | | Outflow | 104 | 32 | 112 | 132 | 58 | 4 |

| Parameter | Units | ID | Cell 4 | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Avg | Std dev | Median | Max | Min | n |
| **TSS** | **mg/L** | Inflow | 2.2 | 0.3 | 2.0 | 2.4 | 1.9 | 3 |
| | | Outflow | 1.4 | 1.6 | 0.3 | 2.5 | 0.3 | 3 |
| **TDS** | **mg/L** | Inflow | 426 | 99 | 426 | 496 | 356 | 2 |
| | | Outflow | 476 | 51 | 476 | 512 | 440 | 2 |
| **TKN** | **mg/L** | Inflow | 1.2 | 0.2 | 1.2 | 1.3 | 1.0 | 2 |
| **TKN** | **mg/L** | Outflow | 1.4 | 0.2 | 1.4 | 1.5 | 1.2 | 2 |
| **$NO_3$+$NO_2$** | **mg/L** | Inflow | 0.05 | 0.04 | 0.05 | 0.08 | < 0.05 | 2 |
| | | Outflow | < 0.05 | 0.00 | < 0.05 | < 0.05 | < 0.05 | 2 |
| **$NH_4$** | **mg/L** | Inflow | 0.07 | 0.00 | 0.07 | 0.07 | 0.07 | 2 |
| | | Outflow | < 0.05 | 0.00 | < 0.05 | < 0.05 | < 0.05 | 2 |
| **TOC** | **mg/L** | Inflow | 43 | 4 | 43 | 45 | 40 | 2 |
| | | Outflow | 46 | 2 | 46 | 47 | 45 | 2 |
| **Hardness** | **mg/L** | Inflow | 231 | 6 | 230 | 237 | 225 | 3 |
| | | Outflow | 249 | 15 | 246 | 265 | 236 | 3 |
| **Total Mg** | **mg/L** | Inflow | 18 | 0 | 18 | 18 | 18 | 3 |
| | | Outflow | 21 | 1 | 21 | 23 | 20 | 3 |
| **Total Ag** | **µg/L** | Inflow | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 3 |
| | | Outflow | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 3 |
| **Total As** | **µg/L** | Inflow | 1.7 | 0.2 | 1.6 | 1.9 | 1.6 | 3 |
| | | Outflow | 2.1 | 0.1 | 2.0 | 2.3 | 2.0 | 3 |
| **Total Cd** | **µg/L** | Inflow | < 0.3 | 0.2 | < 0.3 | 0.3 | < 0.3 | 3 |
| | | Outflow | < 0.3 | < 0.3 | < 0.3 | < 0.3 | < 0.3 | 3 |
| **Total Cr** | **µg/L** | Inflow | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 3 |
| | | Outflow | < 0.7 | < 0.7 | < 0.7 | < 0.7 | < 0.7 | 3 |
| **Total Cu** | **µg/L** | Inflow | 1.2 | 0.5 | 1.4 | 1.6 | < 1.2 | 3 |
| | | Outflow | 1.3 | 0.3 | 1.4 | 1.5 | < 1.2 | 3 |
| **Total Ni** | **µg/L** | Inflow | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 3 |
| | | Outflow | < 0.5 | < 0.5 | < 0.5 | < 0.5 | < 0.5 | 3 |
| **Total Pb** | **µg/L** | Inflow | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 3 |
| | | Outflow | < 0.8 | < 0.8 | < 0.8 | < 0.8 | < 0.8 | 3 |
| **Total Se** | **µg/L** | Inflow | < 1.0 | 0.5 | < 1.0 | 1.2 | < 1.0 | 3 |
| | | Outflow | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | 3 |
| **Total Zn** | **µg/L** | Inflow | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 3 |
| | | Outflow | < 4.0 | < 4.0 | < 4.0 | < 4.0 | < 4.0 | 3 |
| **pH** | **units** | Inflow | 7.90 | 0.05 | 7.91 | 7.95 | 7.82 | 10 |
| | | Outflow | 7.75 | 0.15 | 7.71 | 8.10 | 7.62 | 10 |

| Parameter | Units | ID | Cell 4 | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Avg | Std dev | Median | Max | Min | n |
| **Temp** | **˚C** | Inflow | 33.5 | 3.6 | 22.6 | 26.5 | 16.5 | 10 |
| | | Outflow | 20.9 | 3.7 | 21.7 | 25.0 | 15.4 | 10 |
| **DO** | **mg/L** | Inflow | 5.7 | 1.0 | 6.1 | 6.5 | 3.7 | 8 |
| | | Outflow | 4.0 | 2.1 | 4.4 | 8.0 | 1.5 | 8 |

### 3.2.2 General Water Quality Parameters

*NTC-15*

For both the calibration period and verification periods, mean alkalinity concentrations decreased from inflow to pre-berm stations (297 to 223 mg/L and 284 to 242 mg/L, respectively). Mean alkalinity levels increased from pre-berm to outflow stations during the calibration period. During the verification period we observed the reverse trend, with alkalinity declining from pre-berm to cell outflow locations.

Concentrations of turbidity, color, total suspended solids (TSS) and total dissolved solids (TDS) sampled during the verification period all decreased from the inflow to the pre-berm locations. Suspended solids, turbidity, and color continued to decrease after the passage through the berm, but dissolved solids increased slightly (638 mg/L to 656 mg/L) after berm treatment. Turbidity, color and TDS were not analyzed during the calibration period.

During both the calibration period and the verification periods, specific conductivity and Ca decreased from inflow to pre-berm stations. No further decline in Ca was observed following the berm. Iron, which was sampled only during the verification period, followed the same pattern as specific conductivity, first declining in the wetland but then increasing from pre-berm to outflow locations.

We observed little change in nitrogen and nitrate + nitrite (NOx) concentrations in the SAV/LR, but we did observe a decline in ammonia levels.

Concentrations of potassium, magnesium, sodium, silica, sulfate, chloride and total organic carbon (TOC) did not change from inflow to outflow locations during the verification period. Aluminum, cadmium, chromium, nickel, lead, selenium, silver and zinc were below minimum detection limits during this period.

*STC-9*

As was noted in NTC-15, alkalinity decreased from inflow to pre-berm effluent locations during both the calibration period and the verification periods. Alkalinity either increased, or remained stable from pre-berm to outflow locations.

Turbidity and TSS did not change significantly from inflow to outflow locations during the verification period. However, we did observe reductions in both TDS and color during passage through the SAV/LR wetland.

Removal of Ca was pronounced within the test cell. Calcium concentrations decreased by ~50% from the inflow to the post-berm outflow during the calibration and verification periods. Iron concentrations were low at all sampling points along the STC-9 gradient.

Nitrogen species in STC-9 behaved similarly to those in NTC-15, with a marked reduction in ammonia observed.

As observed in NTC-15, concentrations of potassium, magnesium, chloride and total organic carbon (TOC) did not change from inflow to outflow regions, and aluminum, cadmium, chromium, nickel, lead, selenium, silver and zinc were found to be below minimum detection limits.

*Cell 4*

During the Cell 4 verification period, inflows to the wetland contained lower concentrations of alkalinity, specific conductivity, color, Fe, Ca, Na, $SO_4$, Cl, total dissolved solids (TDS), TKN, and $NH_4$ than were observed for the test cells during their verification sampling. These differences likely were due to the influx of the Loxahatchee Refuge surface water to STA-1W during late November and December 2001 (note that neither EAA runoff, nor Lake Okeechobee waters, were available as in input source during this period). For example, average alkalinity for the north and south test cell inflow was 279 mg/L compared to an average of 183 mg/L in Cell 4 inflow several months later; hardness in the test cell inflow water was almost 30% higher than Cell 4 inflow water. Also, alkalinity decreased from inflow to outflow for the test cells during the verification period (8/17 to 9/29/01), but concentrations did not change from inflow to outflow for Cell 4 during its verification period (12/7 to 12/31/01). Instead concentrations of these constituents declined during the verification period, which reflects their gradual dilution.

Specific conductivity increased from a mean of 681 mg/L in the Cell 4 inflow to 755 mg/L in the outflow. However, outflow raw data collected during the four-week assessment varied considerably (1020 to 610 mg/L). Sodium, $SO_4$, Mg, Cl, TDS, and hardness also showed an increase from inflow to outflow in Cell 4. By contrast, concentrations of these parameters in the test cells, with the exception of Mg, either remained constant or declined.

Calcium levels were relatively low in the Cell 4 inflow (68 mg/L) in comparison to the average of the north and south test cell inflow data (95 µg/L). Average calcium concentrations did not change during passage through Cell 4.

Nitrogen species in Cell 4 behaved similarly to the test cells, with a reduction in ammonia observed as the water flowed through the cell. Also similar to the test cells, average Ag, Cd, Cr, Ni, Pb, Se, and Zn levels were below detection limits for both inflow and outflow of Cell 4.

Cell 4 and test cell waters were analyzed by the FDEP laboratory for chlorinated herbicides (e.g., 2,4-D) and organonitrogen and organophosphorus pesticides. Of the suite of compounds, only atrazine and ametryn were detected (and at low concentrations) in the inflow and outflow waters of each of the wetlands.

# Section 4: Full-Scale SAV/LR Conceptual Design

Using the findings from our evaluation and monitoring efforts, we developed a conceptual design for a full-scale SAV/LR system that would be used to treat the predicted P loadings to STA-2. In this section, we provide conceptual SAV/LR system designs for both Post-BMP and Post-STA configurations. To accomplish this, we first developed and calibrated a model (PMSAV) that capitalizes on key biogeochemical and hydraulic process information. We then used the model to develop a design scenario in which an SAV community is deployed within the STA-2 footprint in a hydraulically "optimized" fashion.

## 4.1 Description of the Process Model for SAV (PMSAV)

The DBE dynamic simulation model for SAV systems is called the Process Model for Submerged Aquatic Vegetation, or PMSAV. The goal for PMSAV development was a compact symbolic and mathematical representation of essential hydraulic and phosphorus removal processes in SAV systems. The model enables a predictive capability for the performance of future SAV systems that will in all likelihood operate with different conditions (pulsed inflows, higher influent concentrations, and improved internal hydraulics) than those observed in SAV datasets during the past years.

Some significant features of PMSAV include the following:

- Representation of two P removal pathways: a biologically mediated pathway and a sedimentation pathway. The biologically mediated pathway aggregates plant uptake and coprecipitation processes. The sedimentation pathway models settling of the particulate TP fraction.
- Aggregated representation of sediment burial and recycle processes.
- Inclusion of biomass and sediment storage relationships from DBE mesocosm and test cell data.
- A hydraulic model specifically aimed at modeling the well-documented detrimental effects of hydraulic short-circuiting in Cell 4. This feature enables estimation of "intrinsic" rate constants from the Cell 4 data that would otherwise be tainted if the

short-circuit were not explicitly modeled. The “intrinsic” constants are the most appropriate constants to use for future STA design efforts.

### 4.1.1 Model Description and Equations

PMSAV is comprised of three modeling components: hydrologic, hydraulic and P-cycling components. The hydrologic component simulates the overall daily water balance in the modeled wetland. The hydraulic component simulates the internal movement of water through the treatment cell using a modified tanks-in-series (TIS) approach. The P-cycling component simulates significant phosphorus processes in SAV wetlands including biologically mediated removal, sedimentation, sediment recycle, and long-term P burial.

*Hydrologic Water Balance*

Figure 4-1 shows a diagram illustrating the wetland water balance. Table 4-1 summarizes the source or equation used for each flow and for water storage (depth) in the hydrologic model. The table also shows average values of these parameters from the calibrated model. These values will be discussed further along with simulation results in a subsequent section. Table 4-2 summarizes the description and values for all constants in the water budget formulation. The procedure for calibrating the water balance model will also be discussed in a subsequent section.

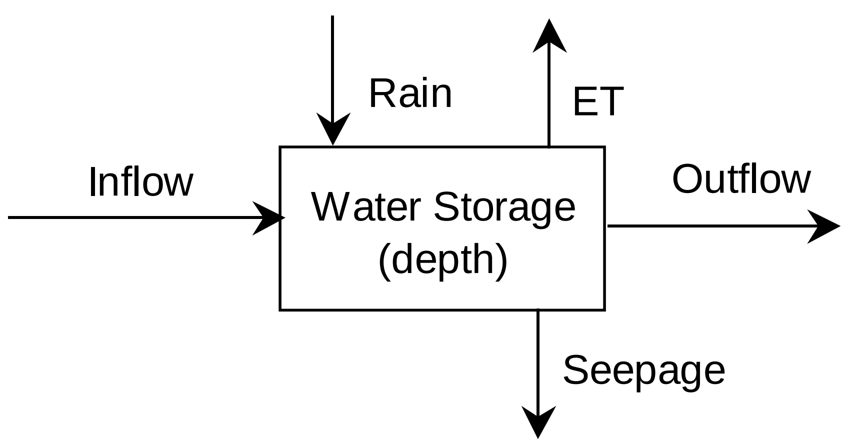



**Figure 4-1.** The wetland water balance

District-provided daily inflow, rain, and evapotranspiration time series are used as input datasets. Seepage is calculated with a Darcy flow equation that assumes the receiving body (which could be either groundwater or the canal along the western levee) is 0.5-m below the bottom of Cell 4. Daily outflow is calculated using a form of the depth-dependent flow equations suggested by Kadlec and Knight (1996). It should be noted that the forms of both seepage and outflow equations are borrowed from those in DMSTA.

**Table 4-1.** Summary of equations in the PMSAV water balance.

| | Variable | Symbol | Source or Equation | Avg. Cell 4 Value * |
|---|---|---|---|---|
| Storage | depth | $d$ | $\frac{d(d)}{dt} = q_{in} + ppt - et - s - q_{out}$ | 0.70 m |
| Flows | Inflow | $q_i$ | Input time series from G254 data (equivalent to daily HLR) | 0.124 m / d |
| | Rain | *ppt* | Input time series | 0.004 m / d |
| | ET | *et* | Input time series | 0.004 m / d |
| | Seepage | $s$ | $= K_{seep} (d - d_s)$ | 0.002 m / d |
| | Outflow | $q_o$ | $= K_o\ d^a\ w/A$ (if $d < d_m$ then $q_o = 0$) | 0.121 m / d |

* during January 1998 through October 2000 calibration period

**Table 4-2.** Summary of constants in the PMSAV water balance.

| | Constant | Description | Units | Value |
|---|---|---|---|---|
| Assigned | $A$ | Wetland surface area | $m^2$ | 1.46E6 |
| | $w$ | Average wetland width | m | 700 |
| | $d_m$ | Wetland depth below which there is no outflow | m | 0.4 |
| | $d_s$ | Assumed stage differential for Darcy seepage flow estimation | m | -0.5 |
| Calibrated | $K_{seep}$ | Coefficient for magnitude of seepage flows | 1 / d | 0.002 |
| | $K_o$ | Coefficient for magnitude of wetland outflows | - | 0.75 |
| | $a$ | Exponent for depth dependent hydraulic resistance in outflows | - | 3.5 |

*Hydraulic Processes*

*"Normal" Model*

The normal hydraulic model used for Post-BMP calibrations and for PMSAV in STSOC design mode is the standard tanks-in-series (TIS) formulation.

*Hydraulic model for Cell 4 (Post-STA) calibrations*

DBE's dye tracer studies have identified the significance of short-circuit pathways on P removal in Cell 4. Consequently, the hydraulics component of PMSAV has been formulated with specific features to mathematically model these important processes for post-STA calibration. The Cell 4 hydraulics model enables a more accurate calibration of rate coefficients for TP removal based on the Cell 4 data set.

Figure 4-2 shows a schematic diagram of our model for Cell 4 hydraulic processes. Flow is modeled in the wetland with two parallel pathways: vegetated treatment and non-vegetated short-circuit pathways. The treatment zones are modeled as a three tanks-in-series (TIS) system. The short-circuit zones are modeled as 9 TIS pathway in parallel with the treatment zones. It is assumed that no P removal occurs in the short-circuit zones. There are three points in the hydraulic model at which complete mixing occurs between the two pathways.

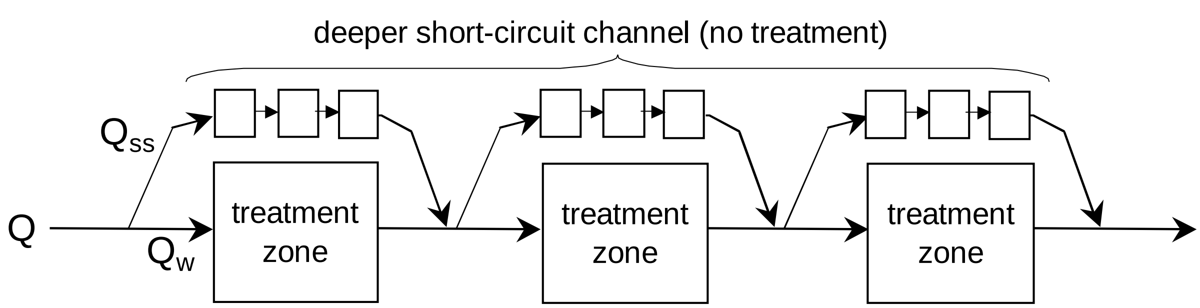



**Figure 4-2**. In addition to the standard TIS formulation, PMSAV has a hydraulics model specifically aimed at modeling Cell 4 hydraulic processes. The Cell 4 hydraulics model accounts for parallel treatment and short-circuiting pathways, with intermittent mixing between the two.

The short-circuit pathway in the model are primarily intended to emulate the prominent zigzag-shaped short-circuit through Cell 4 that was documented in the December 1999 DBE dye tracer assessment. It is not specifically intended to model the myriad of other smaller short-circuit pathways that seem inherent in most wetland hydraulic behavior, but probably captures some of this behavior anyway. The depth in the Cell 4 short-circuit pathway has been measured at over a meter deeper than average Cell 4 depths, and is accordingly prescribed a deeper depth in the model. The higher number of series-connected short-circuit tanks compared to vegetated tanks implies a greater degree of plug-flow through those zones. Mixing between vegetated and short-circuit pathways is an essential aspect of Cell 4's internal hydraulics as evidenced in the C-7 canal, which is a zone of mixing between the general north-south flow through vegetated zones and the zigzag flow of the documented short-circuit.

This model geometry assumes that Cell 4 would behave like a 3 TIS system if the prominent short-circuit were non-existent. In the first Cell 4 tracer assessment, DBE measured the hydraulic efficiency of Cell 4 as similar to a TIS=1.3 system (DBE, 2002). Therefore, the Cell 4 hydraulic model hypothesizes that the difference between Cell 4 acting as a 3 TIS system and as a 1.3 TIS system is caused by the fraction of total flow routed through the short-circuit pathway. Kadlec and Knight (1996) have suggested that TIS=3 is a good representative value for "typical" surface flow wetlands. Additionally, we validated the TIS=3 assumption during model calibration, where we also evaluated this model (with short-circuiting) using wetland TIS values of 2 and 4, both of which yielded reduced calibration effectiveness.

Mathematically, there are two parameters required to define the behavior of the hydraulic model shown in Figure 4-2: the fraction of wetland area occupied by the short-circuit and the fraction of flow diverted through the short-circuited pathway. The fractional area is an input constant, but the fractional flow is calculated based on depth-dependent relationships.

The equations that describe flow through vegetated and open-channel regions suggest that the flow proportioning between Cell 4's treatment and short-circuit zones may be dynamic and depth dependent. It is likely that flow through Cell 4's short-circuit behaves as an open-channel and could therefore be described with Manning's equation as:

$$Q_{ss} = \frac{1}{n} r^{2/3} S^{1/2} (A\ f_{area})$$

where $Q_{ss}$= flowrate through the short-circuit area ($m^3$/ d)

$r$ = hydraulic radius of short-circuit channel

$$= \frac{((d + d_{ss})\ w\ f_{area}}{(2\ (d + d_{ss}) + wf_{area}}$$

$n$ = manning's number

$S$ = bed slope (constant)

$f_{area}$ = fractional area occupied by the short-circuit

$d_{ss}$ = additional depth in short-circuit channel below ground level of treatment region

Hydraulic resistance through densely vegetated wetland zones is not constant (as in open channel flow), but tends to decrease with increasing water depth (Reed, et al 1998, Kadlec and Knight 1996). Accordingly, Kadlec and Knight (1996) have proposed the following general form for estimating flow through densely vegetated areas:

$$Q_w = b_1\ d^a\ S\ (A (1 - f_{area}))$$

where $Q_w$ = flowrate through wetland areas ($m^3$/ d)

$b_1$ = scalar constant (typically in the range of 1-5 e7)

$a$ = exponent for depth dependent flow (see Table 4-2)

Combining these two equations and simplifying, the fractional flow through short-circuited areas ($f_{flow}$) can be represented as follows:

$$f_{flow} = \frac{Q_{ss}}{Q_{ss} + Q_w}$$

$$= \frac{r^{2/3}}{r^{2/3} + \dfrac{c\ d^a}{(f_{area}^{-1} - 1)}}$$

where $c = n\ b_1\ S^{1/2}$

The preceding equation suggests the potential for depth-dependent proportioning of flow between treatment and short-circuiting zones in Cell 4. The relationship suggests that the fractional flow through the wetland increases with increasing water depths in Cell 4 (the shallower the water, the more the effects of short-circuiting). When linked with the P removal model, this relationship results in improved P removal at deeper water depths due to less short-circuited flows (more treated flows). Table 4-3 summarizes the calibration coefficients represented in this equation. The parameter $f_{flow}$ in Table 4-3 was a calculated parameter and not a calibration coefficient, but is shown here for reference.

**Table 4-3.** Summary of coefficients and parameters for Cell 4 hydraulic model.

| Constant | Description | Units | Value |
|---|---|---|---|
| $f_{area}$ | Fraction of total wetland area occupied by the short-circuit channel | - | 0.08 |
| $d_{ss}$ | Additional depth in short-circuit channel below ground level of treatment region | m | 1.2 |
| $c$ | Combined constant that determines short-circuit flow distribution. | - | 50 |
| $f_{flow}$ | Fraction of total wetland flow passing through the short-circuit channel | - | 0.44* |

* Average value of a dynamic time history

*P Cycling Processes*

Figure 4-3 shows a diagram of P removal processes modeled in PMSAV. These processes are modeled in each of the 'treatment zones' shown in Figure 4-2.

Table 4-4 shows the equations and sources of data for the storages and flows in the P-removal model. Table 4-5 summarizes the eight constants that require calibration in this model. As with previous tables presented in this section, the numeric values presented in these tables will be discussed further in subsequent sections.

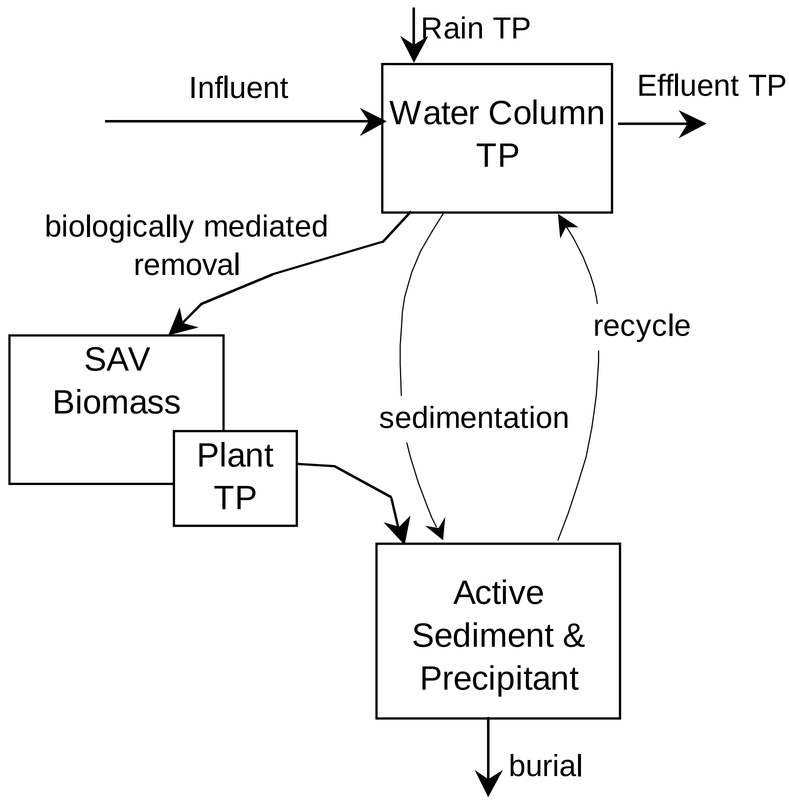



**Figure 4-3.** Process diagram for P-removal as modeled in PMSAV's treatment zone.

There are three active storages of P modeled in PMSAV: water column, biomass tissue, and active sediment storages. The P stored due to burial is also a storage, but it is an inactive long-term deposit. SAV biomass is modeled separately from plant-P, as PMSAV simulates variable P removal as a function of water column concentration (luxury uptake), implying variable plant P concentrations (g-P / g-SAV).

Influent, effluent, rain-based, and seepage flows of phosphorus are calculated using daily water flow rates from the water balance model. Biomass growth is modeled with a modified Monod formulation. This includes a linear growth rate (proportional to biomass standing crop) modified by nutrient (P) limitation. P-limitation is modeled using a standard half-saturation constant formulation. Biomass burial (senescence) is modeled as proportional to the square of the standing crop.

**Table 4-4.** Summary of equations in the PMSAV P-removal model.

| | Variable | Symbol | Source or Equation | Units | Average Values Post-BMP | Average Values Post-STA |
|---|---|---|---|---|---|---|
| Storages | Water column P | $P$<br>$[P]$ | $\frac{d(P)}{dt} = P_{in} + P_{ppt} - P_{out} - U - C + R$<br>$[P] = P/d$ | µg / l | 28 | 21 |
| | Active sediment | $Y$ | $\frac{d(Y)}{dt} = L + C - R - B$ | g / m² | 1.05 | 0.70 |
| | SAV biomass | $SAV$ | $\frac{d(SAV)}{dt} = G - S$ | g / m² | 783 | 685 |
| | Plant associated P | $T_p$ | $\frac{d(T_p)}{dt} = U - L$ | mg-P / kg | 2119 | 1709 |
| Flows | Influent P concentration | $[P_{in}]$ | Input time series from weekly composite TP samples | µg / l | 80 | 59 |
| | P in influent | $P_{in}$ | $= q_i \bullet [P_{in}]$ | g-P / m² / yr | 3.79 | 1.97 |
| | P in effluent | $P_{out}$ | $= q_o \bullet [P]$ | g-P / m² / yr | 1.20 | 0.67 |
| | P with rain | $P_{ppt}$ | $= ppt \bullet [P_{ppt}]$ | g-P / m² / yr | 0.02 | 0.02 |
| | P with seepage | $P_{seep}$ | $= s \bullet [P]$ | g-P / m² / yr | 0.00 | 0.02 |
| | Biomass growth | $G$ | $= K_g \bullet SAV \bullet \frac{[P]}{[P] + [K_{P-1/2}]}$ | g-SAV / m² / yr | 2281 | 1727 |
| | Biomass burial (senescence) | $S$ | $= K_s \bullet SAV^2$ | g-SAV / m² / yr | 2199 | 1696 |
| | Biomass uptake | $U$ | $= (K_u \bullet [P]) \bullet G$<br>where $(K_u \bullet [P]) >= 700$ mg-P/kg | g-P / m² / yr | 5.73 | 3.04 |
| | P sedimentation | $C$ | $= K_c \bullet [P]$ | g-P / m² / yr | 0.57 | 0.39 |
| | Biomass P burial | $L$ | $= {T_p}/{SAV} \bullet S$ | g-P / m² / yr | 4.99 | 3.17 |
| | Sediment P recycle | $R$ | $= g \bullet (1 - b) \bullet Y$ | g-P / m² / yr | 3.68 | 1.88 |
| | Sediment P burial | $B$ | $= g \bullet b \bullet Y$ | g-P / m² / yr | 1.58 | 1.48 |

| **Table 4-5.** Summary of calibration constants for PMSAV. | | | | | |
|---|---|---|---|---|---|
| | **Constant** | **Description** | **Units** | **Post-BMP Value** | **Post-STA Value** |
| Calibrated | $K_g$ | Intrinsic growth rate | 1 / yr | 5.6 | 5.6 |
| | $K_{P-1/2}$ | Half saturation constant for P as limiting nutrient in biomass growth | μg / l | 25 | 25 |
| | $K_s$ | Biomass burial coefficient | $m^2$ / g-SAV / yr | 0.0035 | 0.0035 |
| | $K_u$ | Luxury uptake coefficient | $m^3$ / g-SAV | 0.08 | 0.08 |
| | $K_c$ | Sedimentation coefficient | m / yr | 20 | 20 |
| | $g$ | Sediment turnover rate | 1 / yr | 5 | 5 |
| | $b$ | Sediment burial fraction | - | 0.30 | 0.42 |

Biologically mediated removal is a lumped pathway accounting for both P uptake and coprecipitation processes. Plant P storage assumes an instantaneous removal rate proportional to the product of water column P concentration and standing crop biomass. The instantaneous uptake rate (the parenthetical term in the 'biomass uptake' equation in Table 4-4) is a piecewise linear equation. At very low ambient P concentrations, P is limiting and uptake occurs to maintain minimum tissue P content. At higher ambient P concentrations, P is not limiting and luxury uptake occurs. It is assumed in the model that phosphorus is lost from biomass tissue based on the daily rate of burial and daily average tissue-P concentration.

The sedimentation pathway simulates settling of particulate phosphorus, which accounted for between 15-25% of TP removal in Cell 4. This pathway is modeled as a first-order process proportional to the water column TP concentration. This term can be set to zero when modeling systems with negligible particulate P inflows.

P recycle from the active sediment storage is assumed to be linearly proportional to the amount stored. The long-term burial rate from this storage is also assumed to be linearly proportional to the storage quantity.

*PMSAV Limitations*

As with all models, simulation results should be used and interpreted only in light of a good understanding of the models strengths and weaknesses. There are several limitations in the formulation of PMSAV and we think it is important to state them outright.

In terms of P removal processes, the model has two significant limitations. First, we have chosen to model only TP, rather than a potentially more accurate approach of addressing P speciation. We have much experimental data suggesting the relative ease with which SRP is removed in SAV systems, compared to the more recalcitrant DOP and PP forms. Secondly, while sediment recycle and burial are modeled, internal sediment processes per se are not. We have experimental data suggesting that sediment recycle is more specifically related to relative fractions of organic and calcium-bound materials that are present. While including these processes in PMSAV (both speciation and sediment) would have made for a more accurate representation of our process understanding, it would have also more than doubled model complexity. These processes can be addressed in future PMSAV endeavors beyond this Phase 2 project. It is also important to understand the limitations of the datasets that were used for calibration. The District's input/ output time series of Cell 4 P concentrations are the principle data used for calibration. This dataset is supplemented with DBE measurements of biomass, tissue-P, and sediment that were made (at infrequent intervals) in Cell 4 and numerous other systems within the last few years. We have no time series data on internal process flows, nor is it reasonable to expect that we will have this information in the near future. This makes the calibration task somewhat analogous to mapping the internal traffic flows in a large city when the only available data is the daily flux of entering and leaving vehicles, along with a few spot measurements of internal flows made in several other smaller cities. In the case of PMSAV, we will never say that we have true 'confidence' in the predicted magnitudes of internal flows, but what we can say is that they seem 'sensible' to us based on our studies and experience.

Additionally, the model does not account for large-scale stochastic natural and man-caused events that have occurred during calibration periods that could have substantially influenced TP removal on short and long-term scales. These events include seasonal coot invasions (we noted significant SAV herbivory in Cell 4 during winter months of 2001), numerous construction activities, and tropical storm events.

### 4.1.2 Simulation Procedure

The differential equations (Tables 4-1 and 4-4) were expressed as finite difference equations and coded as a Visual Basic macro within Excel spreadsheets. Input data for the model including data sets and coefficients are contained in the spreadsheets. After input parameters such as calibration coefficients are entered or changed, the simulation macro is executed with a "run" command, which initiates a sequence of reading values from the spreadsheet, executing the simulation code, and returning simulated output to the spreadsheet. Post-processing analysis and graphs of the output data are contained within the same spreadsheet.

### 4.1.3 Calibration Data Sets and Procedure

The objective of PMSAV calibration was to produce two calibrated models that would be used for Post-BMP and Post-STA design exercises. Coefficients from the hydrologic, hydraulic, and P-removal components of PMSAV (Tables 4-2, 4-3, and 4-5) were calibrated with measured inflow and outflow data from two SAV systems: Cell 4 and NTC-15. Additionally, we pooled biomass, tissue-P, and sediment data from numerous DBE sampling events in SAV mesocosms and Cell 4 to provide guidelines for reasonable values of these storages in the P-removal model.

*Cell 4 Data Sets*

Coefficients in the hydrology model (Table 4-2) were calibrated to Cell 4 inflow, outflow, and depth data for the period of January 1, 1998 through October 9, 2000. Data from before January 1, 1998 may not be representative of long-term performance due to start-up (grow-in) artifacts. Data after October 2000 contains significant secondary outflows through the G309 structure, which would significantly complicate calibration (beyond the scope of this effort). Coefficients in the Cell 4 hydraulic model (Table 4-3) were calibrated to data collected in our first Cell 4 dye tracer assessment that was conducted between December 16, 1999 and January 14, 2000.

Phosphorus removal coefficients for the Post-STA model (Table 4-5) were calibrated to Cell 4 data from the period of January 1, 1998 through September 30, 2001 (1368 days). Starting the calibration period in 1998 eliminated start-up artifacts that may have been present in the data set for previous years. Ending the calibration period in September 2001 utilized the most complete usable data that was available at the time of calibration. Input (G254) and output (G256) flow data were provided by the District, on January 18, 2001. We used the District's record of weekly composite TP samples for influent and effluent TP concentrations. A daily inflow time series for TP concentrations was constructed by assuming that the value of a composite measurement applied to all previous days up until the last measurement date.

The Cell 4 input dataset also required modification to accommodate an unforeseen operational change in Cell 4 hydrologic management. Beginning in October 2000, Cell 4 discharged significant outflows through the G309 structure on a regular basis. These outflows presented two modeling difficulties for PMSAV. First, PMSAV was originally formulated to model only one outflow and would require significant modifications to simulate two outflows. Secondly, TP data were not available for G309 outflows, making direct calibration of modeled G309 outflows impossible. Following the recommendation of the District, an input dataset was synthesized for this period on the assumption that G309 flows behaved as untreated short-circuited outflows. Mathematically, this corresponds to subtracting G309 outflows from the measured G254 inflows to create a new synthetic G254 inflow dataset.

*NTC-15 Data Sets*

The Post-BMP model (Table 4-5) was calibrated to NTC-15 data from the period of July 1, 2000 through September 14, 2001 (440 days). This period includes the STSOC verification period, which occurred August 17-31, 2001. In April 2000, a limerock berm was constructed in NTC-15. NTC-15 was re-flooded in late-April after berm construction was completed. Our calibration period begins 2-½ months after re-flooding and concludes with the end of our test cell monitoring period. For Post-BMP calibration, we use only the pre-berm footprint of NTC-15.

Hydrologic data for the model were provided by DBE field measurements. During the calibration period, the inflow orifice to NTC-15 was changed three times: a 1" orifice beginning 6/29/00, a 1.5" orifice beginning 9/15/00, and a 2" orifice beginning 6/1/01. DBE measured flow rates from the NTC-15 inflow distribution manifold frequently (but at irregular intervals) during the calibration period using a bucket and stopwatch method. This provided between 13 and 17 direct flow measurements for each orifice size. For the model's NTC-15 inflow dataset, we used the average value of measured flow for each orifice applied as a constant over the periods that each orifice was used.

We also adjusted the outflow weir elevation several times during the calibration period, which changed wetland depth. We directly measured the water elevation from the two Stephen's depth recorders installed in the cell. We also performed multiple field soundings in NTC-15 to locate the bottom of the water column (top of sediment layer) relative to the Stephen's recorder data. For calibration purposes, NTC-15 depth was assumed to be constant between periods of weir adjustment.

Data for the NTC-15 hydraulic model were provided by multiple DBE dye tracer studies in the SAV test cells. These studies were performed in late 1999 and are discussed in detail in our Final Report document for this project (DBE, 2002)

Inflow and Outflow TP data for NTC-15 were also measured by DBE. Outflow concentrations from the pre-berm footprint were based on a time series of composite samples collected at 3 stations located along the upstream width of the berm.

*Calibration Procedure*

The three PMSAV components were calibrated sequentially. The hydrology model was calibrated first followed by the hydraulics model and finally the P-cycling model. Calibration proceeded in a similar fashion for each of the three model components (hydrologic, hydraulic, and P-removal). Coefficients were manually tuned in a progressive sequence of coarse to fine adjustments until desirable calibration was achieved. Each model component had specifically defined calibration criteria, which are discussed below, that were used to guide coefficient adjustments. Since we did not employ a rigorous mathematical optimization algorithm, our calibrations should be considered "near-optimal".

### 4.1.4 PMSAV Calibration

*Cell 4 Hydrologic Model*

There were four criteria for calibrating the hydrologic model to Cell 4 outflow and depth data:

- The mean simulated wetland depth should be equal to the mean measured depth during the calibration period (± 0.01 m).
- The goodness-of-fit between simulated and measured depth time histories should be maximal. We employed two graphical goodness-of-fit measures: cross-plots of observed and simulated values and plots of model residuals (predictive error) against simulated values (as suggested by Box and Hunter, 1978). From these two graphs, we derive two numeric goodness-of-fit values: the coefficient of determination ($r^2$) and the average absolute residual (mean predictive error).
- The simulated time histories should be as visually similar to the data as possible.
- Net inflows and outflows in the water budget (Figure 4-1) should balance.

Calibrated values for the hydrologic coefficients are given in Table 4-2. Figure 4-4 shows a comparison of simulated verses actual depth data from Cell 4. Note that for a 6-month period beginning in October 2000 (the same month of the start of significant G309 outflows), depth simulations were inexplicably inaccurate (simulated depths 0.2-0.4 m lower than measured). Since accurate depth simulation is essential for the Cell 4 Hydraulics and P-cycling sub-models, we employed a "patch" during this period that forced simulated depths closer to measured values. With the patch in place, the visual fit for the depth simulation (Figure 4-4) is quite good. The patch affected simulated values only between October 2000 and March 2001, which was outside of our defined calibration period for hydrologic parameters.

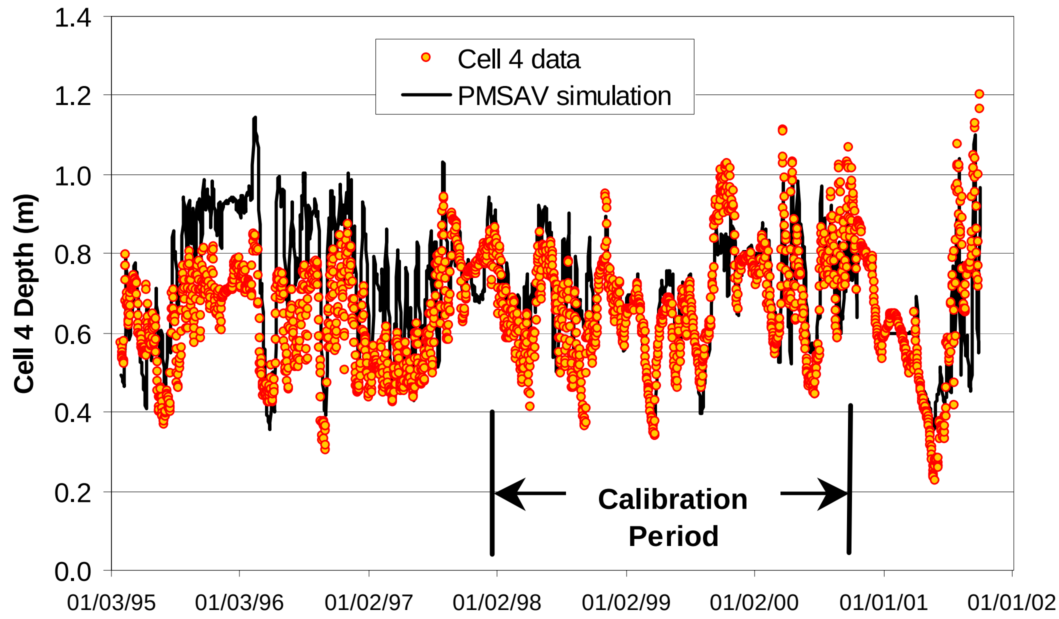



**Figure 4-4.** Simulated versus measured Cell 4 depth.

Figure 4-5 shows a cross-plot of predicted and observed Cell 4 depths during the calibration period. The coefficient of determination for Cell 4 depth simulation was $r^2 = 0.62$. Figure 4-6 shows the simulated depth residuals (simulated – observed) plotted against values of simulated depth. In general, the residuals appear to show a random distribution in relationship to the predicted response (depth), with no bias towards either high or low water depth. This is the desired condition and tends to indicate a well-formulated model (Box and Hunter, 1978). The mean predictive error (average absolute residual) for simulated depth was 0.067 m (~10% of average value of depth).

Figure 4-7 shows a comparison of the time histories of simulated versus observed G256 outflow data (expressed as m / d). Although the graphical goodness-of-fit measures are not shown, the coefficient of determination for Cell 4 outflow simulation was $r^2 = 0.92$ and the mean predictive error was 0.018 m / d (~16% of average value of outflow).

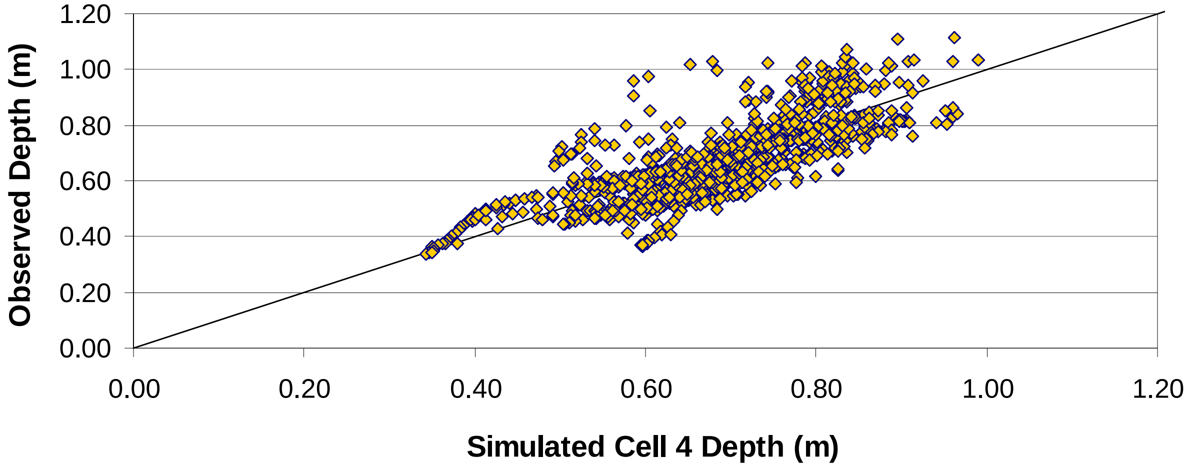



**Figure 4-5.** Cross-plot of simulated and observed Cell 4 depth.

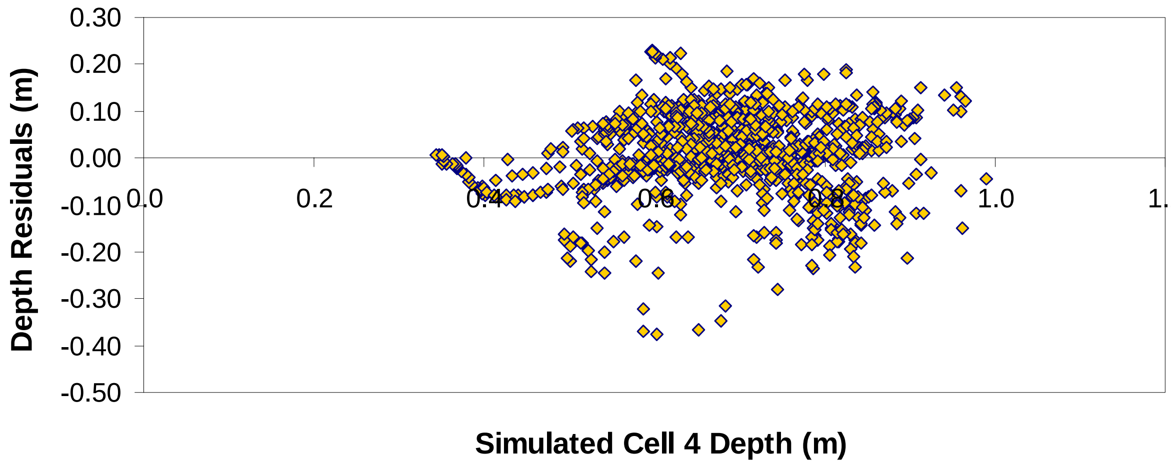



**Figure 4-6.** Residuals from Cell 4 depth simulation plotted against values of simulated depth

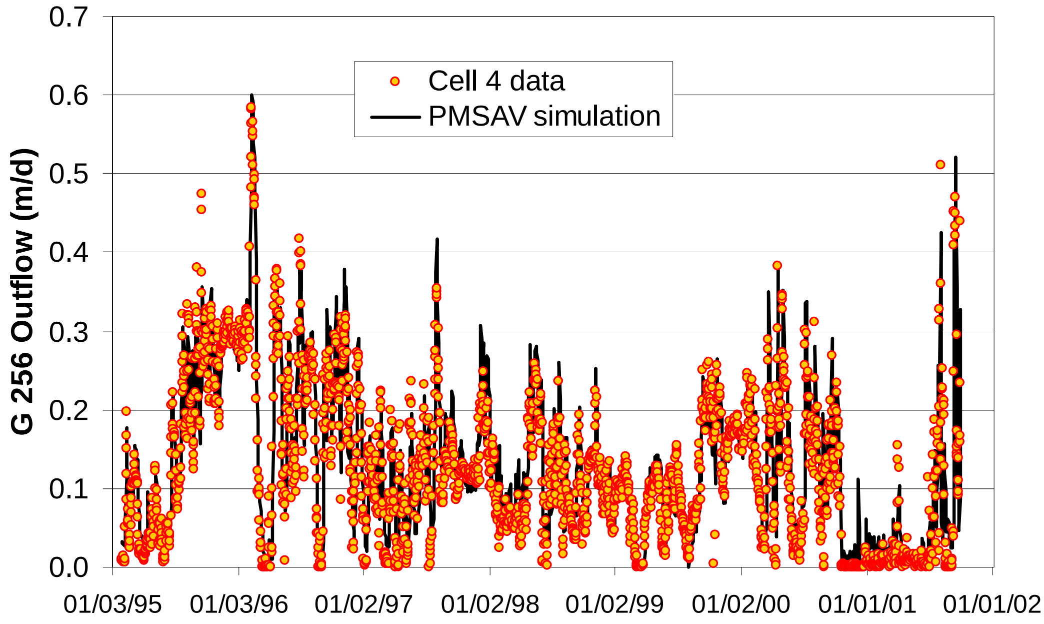



**Figure 4-7.** Simulated versus measured G256 outflow.

*Cell 4 Hydraulic Model*

The Cell 4 hydraulic model was calibrated using data from our December 1999 dye tracer assessment. There were three calibration criteria:

- The coefficient of determination ($r^2$) calculated from a cross-plot of simulated versus measured values of effluent tracer concentration should be as high as possible.
- The simulated tracer response curve should have good visual correlation with the measured tracer response curve.
- The dye recovery fraction should be the same as we measured for that assessment (72%).

Simulations were conducted with the PMSAV Cell 4 hydraulics model by assuming an initial condition of 45.4-kg mass load for the modeled G254 inflow at 10:00 AM on December 16, 1999. This was the exact mass and time of completed dye introduction in our Cell 4 field evaluation. The model simulates "tracer" transport through Cell 4 using the parallel pathway TIS model discussed above (Figure 4-2). In order to account for dye loss in our simulation, a first-order removal term was added. This term is used as a surrogate to account for dye adsorption, chemical transformation processes, and/or long-term dead zone entrapment. The coefficient for first order dye loss was adjusted to yield a 72% dye recovery fraction during the simulation period.

Calibrated values for the hydraulic model coefficients are shown in Table 4-3. A comparison of simulated and measured tracer response curves is shown in Figure 4-8. The Cell 4 hydraulics model provides an excellent fit to the measured data ($r^2$ = 0.99). Note that the calibrated model suggests that during the tracer assessment period, 8% of the Cell 4 area was occupied by short-circuit pathways and that 44% of the total wetland flow passed through these pathways (Table 4-3). Based on our field observations, these seem like sensible values.

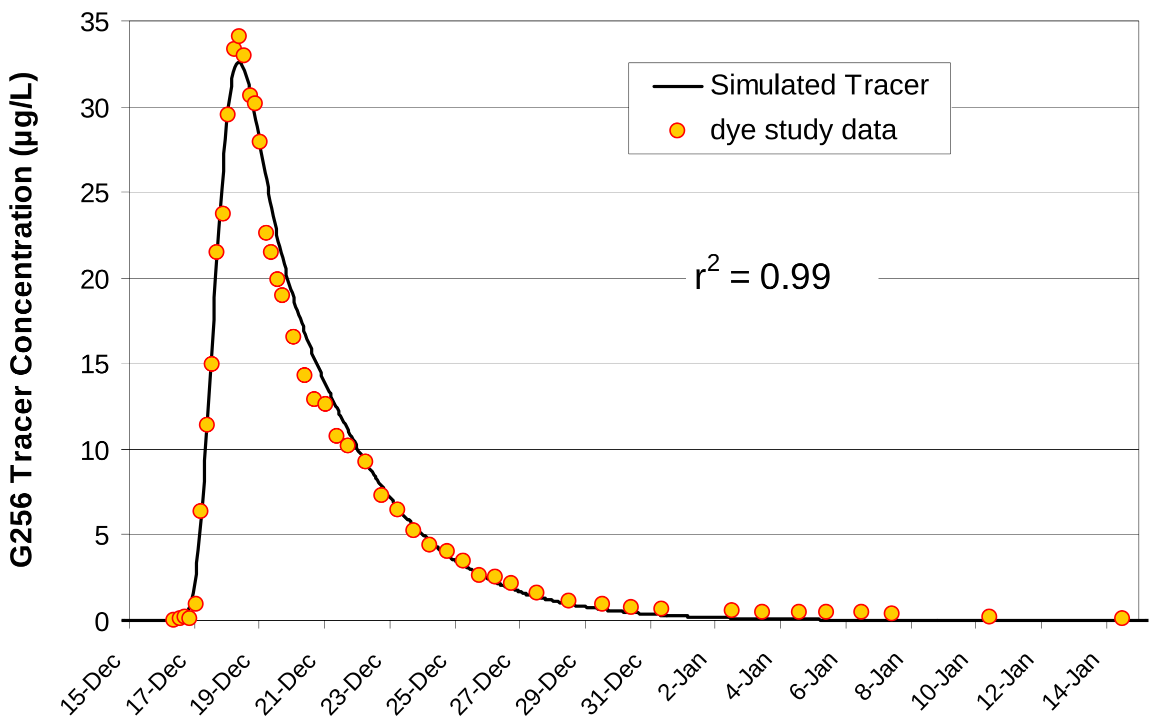



**Figure 4-8.** Calibration of the Cell 4 hydraulic model to DBE's first tracer assessment.

Although calibration to the tracer assessment data was excellent, we opted to decrease the average fraction of short-circuited flow when we performed Post-STA P-removal calibrations with the Cell 4 dataset (next section). While we believe it is essential to account for short-circuiting processes when calibrating P-removal based on the Cell 4 data set, we also believe that it is important to do so in a conservative fashion. It seems possible that a small fraction of the short-circuiting behavior captured in our model may not be due entirely to the prominent zigzag channel (although most probably was), but also caused by natural and inherent smaller pathways through the wetland. Therefore, we decided to de-rate the effects of hydraulic short-circuiting for Post-STA calibrations with Cell 4 data. This was accomplished by using a value of c = 150, rather than the value of c = 50 reported in Table 4-3, which had the effect of decreasing the average short-circuited flow fraction from 44% to 26%. For reference, if the value of c = 150 were employed in the tracer simulations, the resulting data fit would still be acceptable ($r^2$ = 0.70). This assumption was validated during model calibration, where we found improved fit to TP concentration data with a short-circuited flow fraction of 26% compared to 44%.

In terms of P removal calibrations, decreasing the short-circuited flow fraction led to slightly lower values of the calibrated removal constants ($K_u$ and $K_g$), compared to if they were calibrated with short-circuiting fully accounted for. In terms of STA sizing, lower values of calibrated removal constants led to more conservative (slightly larger) predicted STA footprints.

*Post-STA Phosphorus Removal*

There were four criteria for calibrating PMSAV to the Cell 4 data set. These were:

- The simulated flow-weighted mean effluent TP concentration must equal the measured flow-weighted effluent concentration for the calibration period (± 0.2 μg/l).
- The goodness-of-fit between simulated and measured TP time histories should be maximal. We employed two graphical goodness-of-fit measures: cross-plots of observed and simulated values and plots of model residuals (predictive error) against simulated values (as suggested by Box and Hunter, 1978). From these two graphs, we derive two numeric goodness-of-fit values: the coefficient of determination ($r^2$) and the average absolute residual (mean predictive error).
- The simulated means for PMSAV storages (biomass, plant-P, and sediment) must compare favorably with data collected in SAV mesocosms and Cell 4. Since there is considerable scatter in the mesocosm and Cell 4 data (Figure 4-9), we employed a loose criterion such that simulated values fall sensibly within the range of observed values.
- The visual appearance of the simulated TP effluent time history must compare favorably with the measured time history.

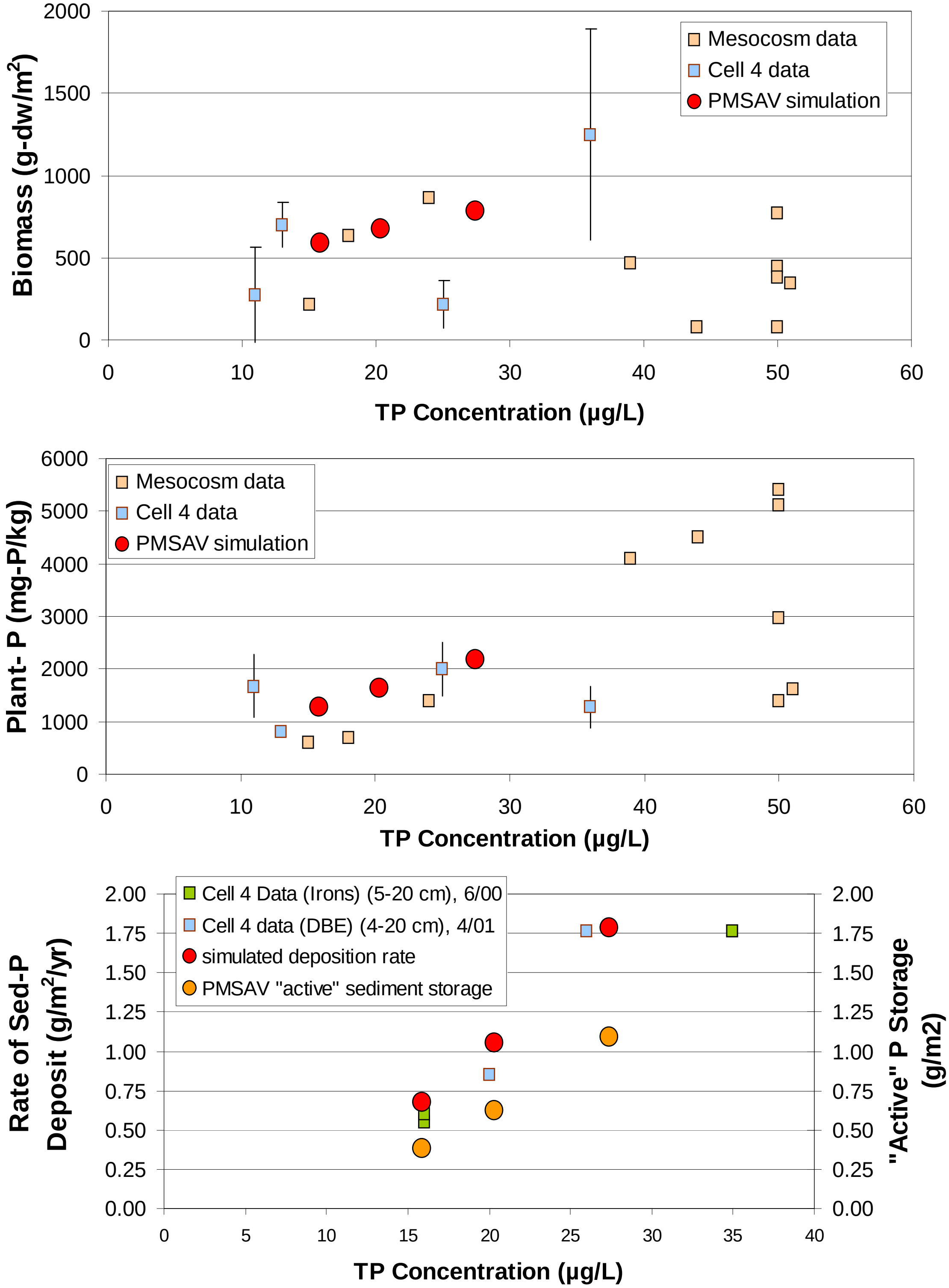



**Figure 4-9.** Simulated values of biomass, plant-P, and sediment-P storages (top to bottom) from the Cell 4 calibration compared to measured data from mesocosms and Cell 4.

The Post-STA simulation was conducted using a 3-year startup period (February 1995 – December 1997) before the calibration period (January 1998 – October 2001). Initial conditions were prescribed for the beginning of the startup period (SAV biomass = 10 g/m$^2$, Sediment P = 0.1 g/m$^2$). The values for initial conditions affected simulated TP values during the startup period, but not during the calibration period. In other words, the Post-STA calibration values were not sensitive to initial condition assumptions.

Calibrated values of the key P removal process parameters for the Post-STA PMSAV calibration are shown in Table 4-5. Figure 4-10 shows a comparison of the simulated and measured effluent TP time histories. For the calibration period, the simulated flow-weighted mean effluent TP concentration was 21 μg/l (flow-weighted mean), which equaled the observed value. Figure 4-11 shows a cross-plot of simulated and observed TP concentrations and Figure 4-12 shows a plot of the model residuals. The coefficient of determination for the calibration period was $r^2$ = 0.31 and the mean predictive error was approximately 6 μg/l. In general, the residuals appear to show a random distribution in relationship to the predicted response (outflow concentration), with no noticeable bias towards either high or low values (Figure 4-12). This is the desired condition and tends to indicate a well-formulated model (Box and Hunter, 1978). When the startup years (1995-1997) are included in the goodness-of-fit measures, $r^2$ decreased to 0.24.

Figure 4-9 shows a comparison of the mean simulated biomass and plant-P and the annual rate of sediment-P accumulation compared to measured values from mesocosm and Cell 4 data. The X-axis of these graphs shows water column ambient TP concentration. The Y-axis shows the values of biomass storage (g-SAV/m2), tissue-P concentration (mg-P/kg-SAV) and sediment-P deposition rate (g-P/m2/yr) that were either measured or simulated at that average water column concentration. Note that simulated values correspond to the average values calculated within each of the three wetland tanks (Figure 4-2) in the PMSAV model during the simulation period. Also note that measured water column concentration data were not available for all biomass or sediment samples collected, so some of these concentration values were estimated. In all cases, the PMSAV-simulated values are within the boundaries of observed values and compare well with field-measurements.

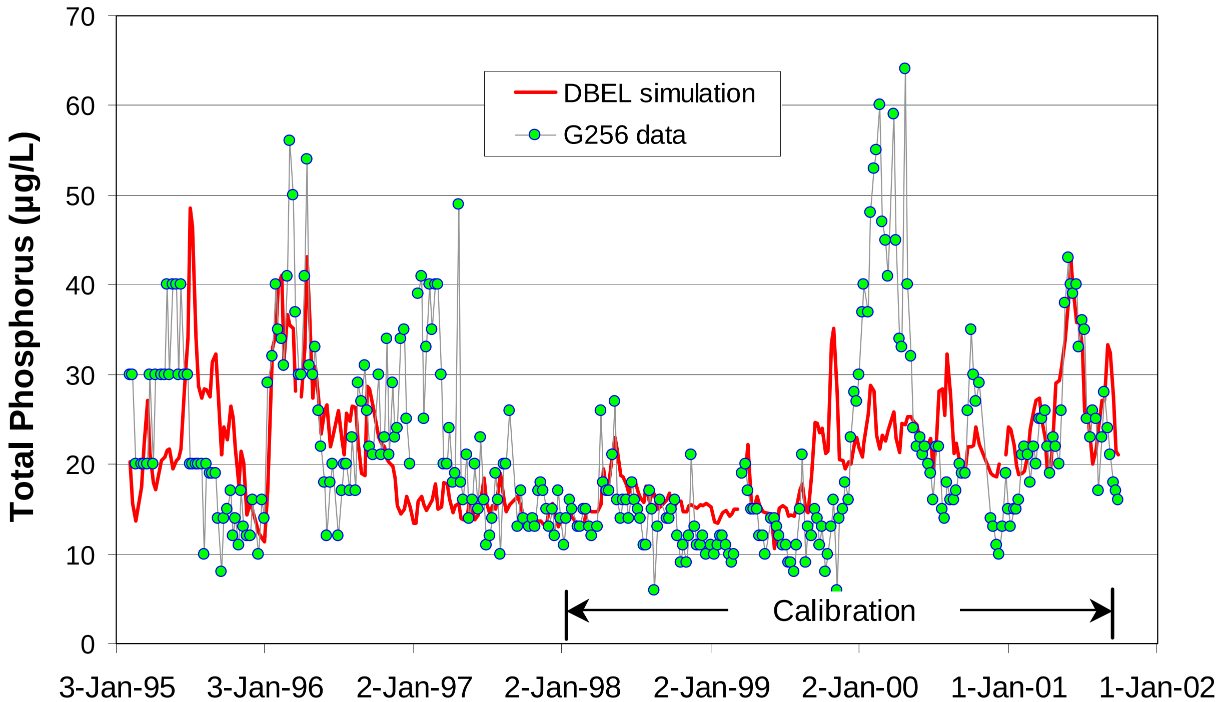



**Figure 4-10.** Post-STA calibration of PMSAV to the Cell 4 data set.

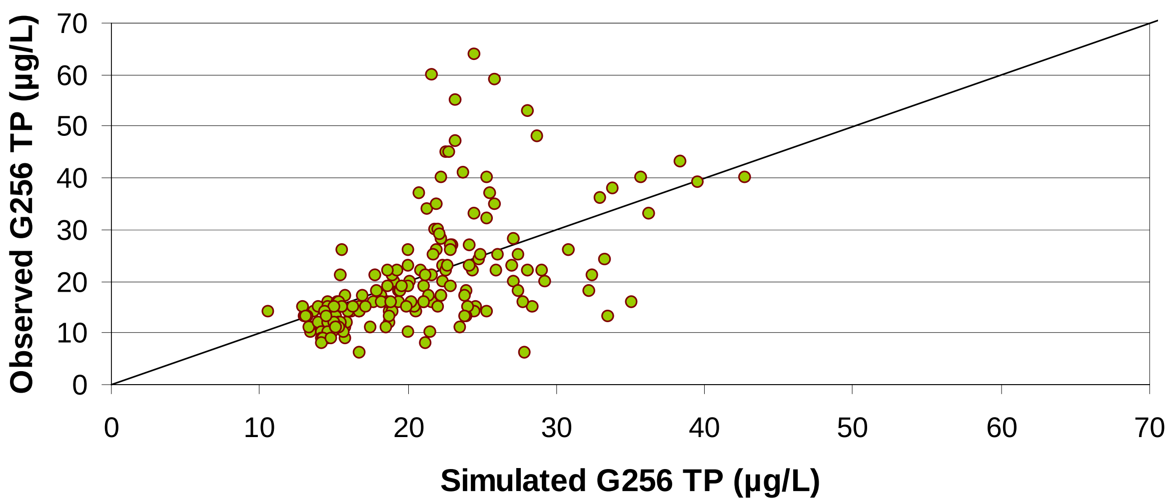



**Figure 4-11.** Cross-plot of Cell 4 simulated and observed outflow TP concentrations.

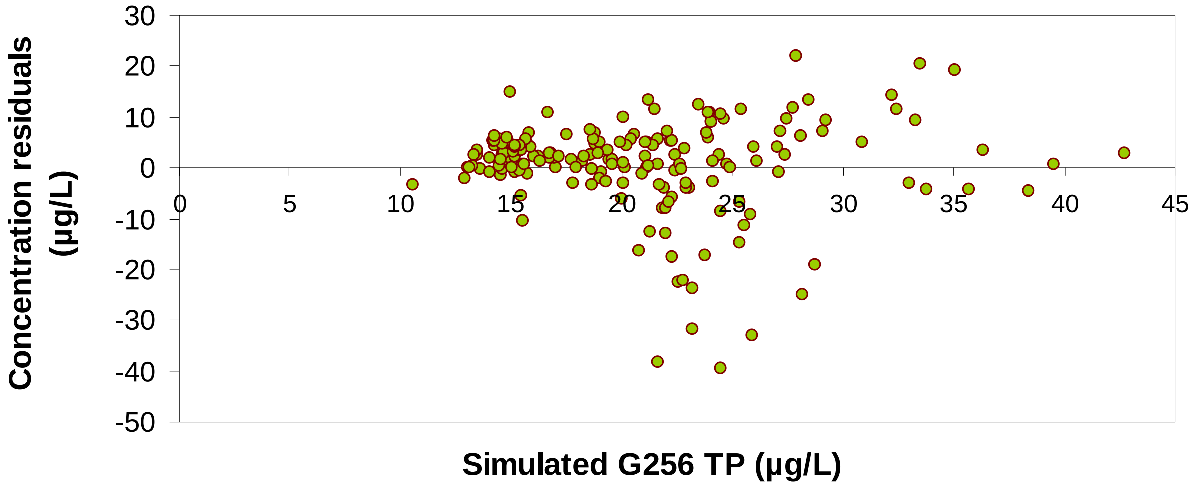



**Figure 4-12.** Residuals from simulation of Cell 4 outflow concentrations.

*NTC-15 Hydrology Model*

The PMSAV hydrology model was modified to accommodate the various weir elevation (stage) changes that occurred throughout the NTC-15 calibration period. Wetland depths were "forced" to match measured NTC-15 depths and outflow water volumes were calculated by difference. As a result, the hydrology model for NTC-15 was not "calibrated", per se, but rather forced to match measured conditions. Figure 4-13 shows the observed and "forced" depth used in NTC-15 simulations.

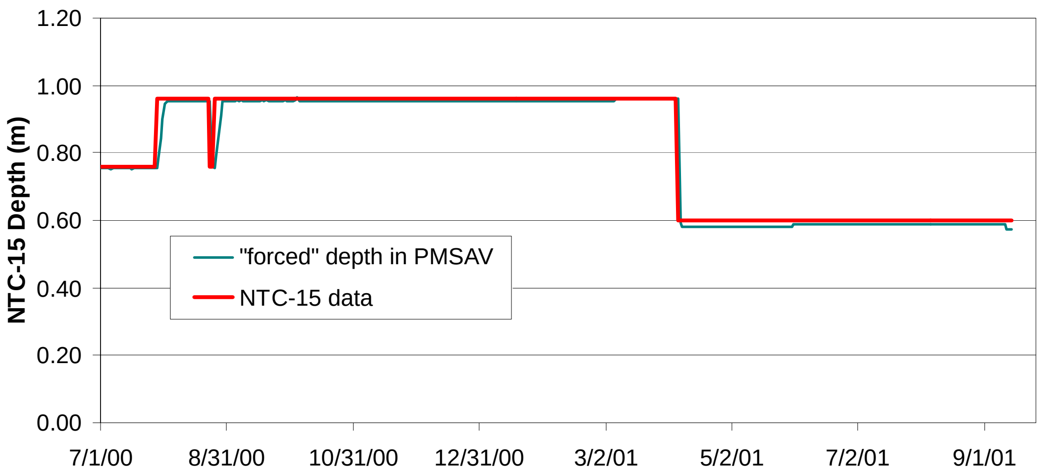



**Figure 4-13.** Observed and simulated depth for NTC-15

*NTC-15 Hydraulic Model*

NTC-15 does not exhibit the blatant hydraulic short-circuiting that is evident in Cell 4. As a result, we did not employ the Cell 4 Hydraulic Model for NTC-15 modeling, but instead used the simpler (and what is becoming standard) TIS approach.

Data measured in the first DBE tracer assessment on the four SAV test cells indicated that their hydraulic efficiency could be represented with TIS values between 1.7 and 3.3 (average value of TIS=2.5), as calculated with the method of moments (DBE 2002). The specific value for NTC-15 from this assessment was TIS = 1.7, the lowest measured. In the time between the tracer assessments and the model calibration period, NTC-15 was partially drained for limerock berm construction, re-flooded, and restocked with vegetation. The point being that we do not have recent hydraulic data that could be used with confidence for hydraulic calibration. Therefore, we have assumed a value of TIS=2 for Post-BMP calibration to NTC-15 data.

*Post-BMP P-Removal*

The calibration criteria to the pre-berm NTC-15 data were identical as discussed above for Post-STA calibration. The Post-BMP calibration was conducted assuming a steady-state condition in NTC-15. Here, we use the term 'steady-state' to imply that the system was past startup and that P removal was due primarily to long-term burial rather than biomass grow-in. Before berm construction (April 2000), NTC-15 had been flooded for over a year and had appearances of a stable SAV community. During berm construction, NTC-15 was partially drained for a 10 day period and was immediately re-flooded. While there were indications of 'burning' on exposed SAV plants during the drained period, there were also indications of healthy and ubiquitous SAV below the 'burned' mats. The Post-BMP calibration period using NTC-15 data initiates approximately 2-½ months after re-flooding and we have assumed that the system was at or close to steady-state at that time. To simulate steady-state conditions in PMSAV, the Post-BMP calibration model was run for several iterations, where average values of model storages (biomass, plant-P, sediment-P) from the previous iteration were used as initial conditions for the next simulation. After several iterations, this technique achieves steady-state conditions and eliminates sensitivity of calibrated values to initial conditions.

Calibrated values for the Post-STA PMSAV calibration are shown in Table 4.5. Note that the principal difference between NTC-15 and Cell 4 calibrations is that the latter had a higher burial fraction coefficient. Figure 4-14 shows a comparison of the simulated and measured effluent TP time histories. For the calibration period, the simulated flow-weighted mean effluent TP concentration was 25 μg/l (flow-weighted mean), which equaled the measured value. Figure 4-15 shows a cross-plot of simulated and observed pre-berm TP concentrations in NTC-15 and Figure 4-16 shows TP residuals from this simulation. The coefficient of determination for the calibration period was $r^2 = 0.67$ and the mean predictive error was approximately 4 μg/l.

Figure 4-17 shows a comparison of the mean simulated biomass, plant-P, and sediment-P compared to measured values from mesocosm and Cell 4 data. The X-axis of these graphs shows water column ambient TP concentration. The Y-axis shows the values of biomass storage (g-SAV/m2), tissue-P concentration (mg-P/kg-SAV) and sediment-P deposition rate (g-P/m2/yr) that were either measured or simulated at that average water column concentration. Note that simulated values correspond to the average values calculated within each of the three wetland tanks (Figure 4-2) in the PMSAV model during the simulation period. Also note that measured water column concentration data were not available for all biomass or sediment samples collected, so some of these concentration values were estimated. In all cases, the PMSAV-simulated values are within the range of observed values and compare well with field-measurements.

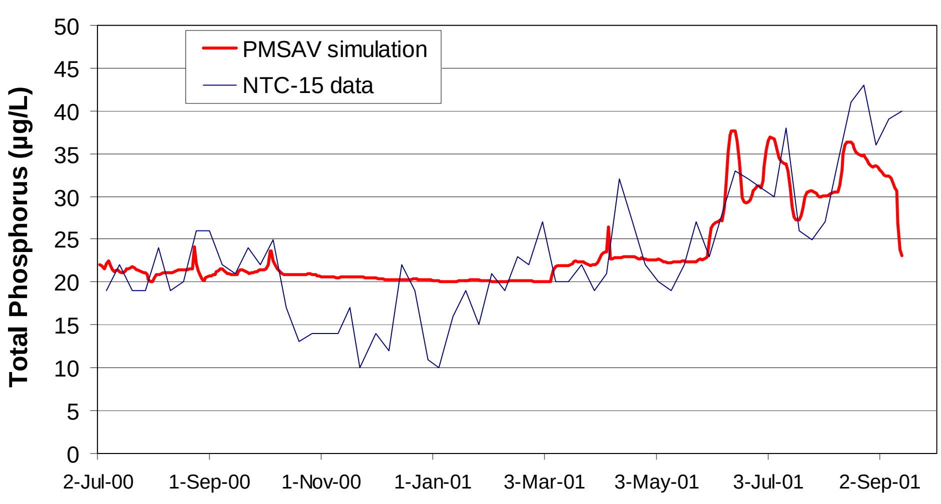



**Figure 4-14.** NTC-15 simulated versus measured effluent TP.

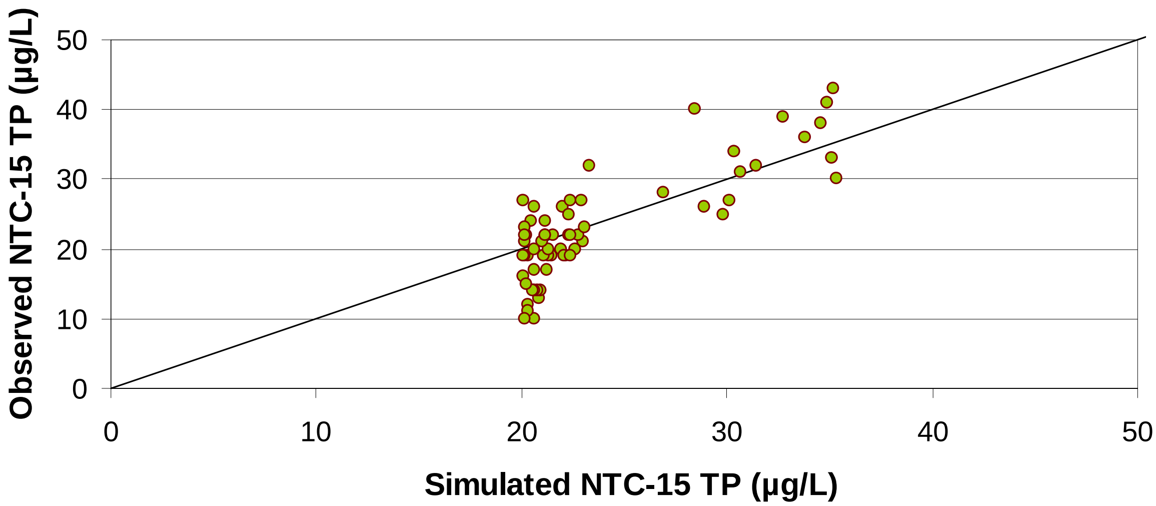



**Figure 4-15.** Cross-plot of NTC-15 simulated and observed pre-berm TP concentrations

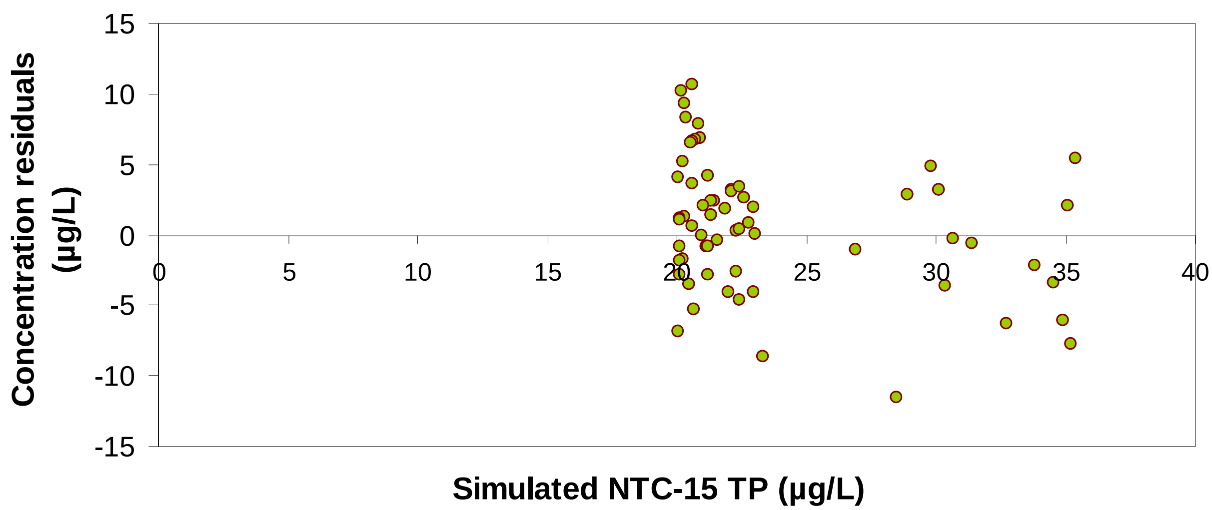



**Figure 4-16.** Residuals from NTC-15 TP simulation

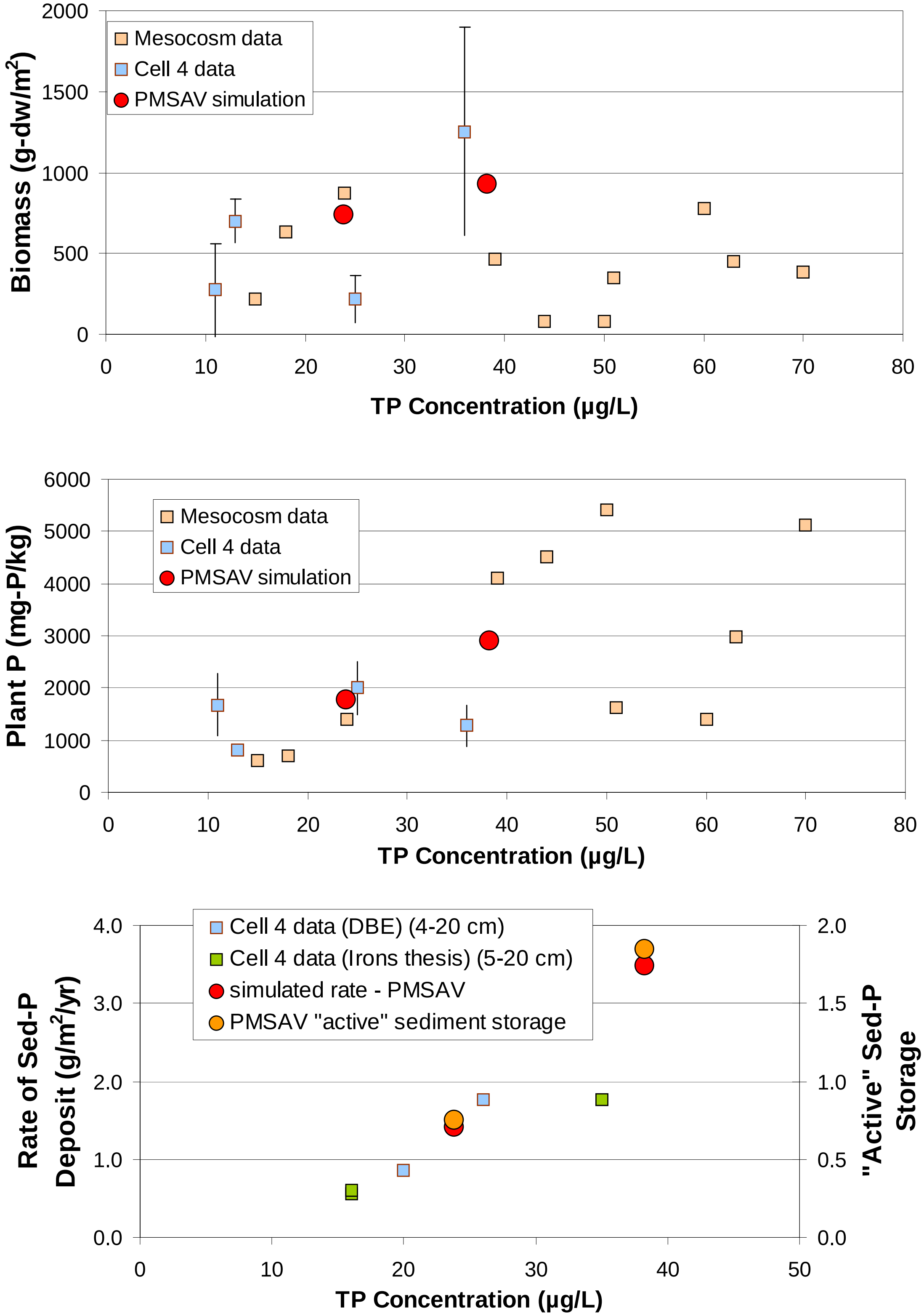



**Figure 4-17**. Simulated values of biomass, plant-P, and sediment-P storages (top to bottom) from the NTC-15 calibration compared to measured data from mesocosms and Cell 4.

### 4.1.5 Sensitivity Analysis

Table 4-6 shows the results of a sensitivity analysis of PMSAV TP predictions to coefficient values. We varied the values for Post-STA (Cell 4) calibration coefficients one-at-a-time by +50% and –50% of their nominal values (see Tables 4-3 and 4-5) and used modified values to predict Cell 4 outflow concentrations. The values in Table 4-6 express the percent change in predicted TP outflow as a result of the new coefficient values. Model parameters are listed from least to most sensitive (top to bottom) in the table.

As could be expected, the most sensitive parameters were related to the biomass removal pathway and burial. Taken together, the biomass growth rate, biomass burial rate, and half-saturation constant determine the simulated standing crop and its turnover rate. While the DBE biomass data (Figures 4-10 and 4-17) is adequate for calibrating standing crop, no data were available to provide insight into turnover rate. If PMSAV will be used for future system performance predictions and footprint sizing, then determination of turnover times is a good area for future model enhancement.

**Table 4-6.** Sensitivity of simulated TP to +/- 50% change in model coefficients using Post-STA calibration and the Cell 4 data set.

| Parameter | Description | Parameter Value | % Change in Simulated Outflow Concentration | |
|---|---|---|---|---|
| | | | - 50% | + 50% |
| g | Sediment turnover rate | 5/yr | - 2 % | +1 % |
| $K_c$ | Sedimentation coefficient | 20 m/yr | + 3 % | - 3 % |
| c | Short-circuit flow distribution | 150 | + 12 % | - 5 % |
| b | Sediment burial fraction | 0.30 | + 18 % | - 11% |
| $K_s$ | Biomass burial rate | 0.0035 $m^2$/g-SAV/yr | - 25 % | + 17 % |
| $K_{P-1/2}$ | Half-saturation constant for P | 25 µg/l | - 25 % | + 18 % |
| $K_r$ | Luxury uptake rate | 0.08 $m^3$/g-SAV | + 30 % | - 15 % |
| $K_g$ | Biomass growth rate | 5.6/yr | + 60 % | - 28 % |

## 4.2 PMSAV Model Simulation for STA Design

### 4.2.1 PMSAV Model for Design

PMSAV was used in design mode to assess Post-STA and Post-BMP design scenarios. For our Post-BMP analysis, the input dataset for PMSAV simulations was the District-provided STSOC Post-BMP data set (flow-weighted mean influent TP concentration of 122 µg/L) for STA-2. For our Post-STA analysis, the input dataset for PMSAV simulations was the District-provided STSOC Post-STA data set (flow-weighted mean influent TP concentration of 50 µg/L).

*PMSAV Formulation*

In design mode, the PMSAV hydrology model (Figure 4-1) was supplemented with a flow bypass feature that diverted a fraction of inflow around the SAV treatment areas. The bypass feature essentially 'chopped the top off' peak flows, leaving flow magnitudes below the bypass threshold unaffected. This feature was used to assess the 10, 20, and 30% bypass scenarios in our STSOC design analysis.

PMSAV has not been formulated to simulate processes that might occur during an extended dry-down event, such as rapid biomass senescence and increased recycle of sediment P. We have, however, added provision for make-up flows for low stage maintenance during prolonged dry spells. This feature is in accordance with District plans for several STA sites and insures that a minimum wetland stage depth is maintained. For our design runs, we set the minimum stage at the ground surface elevation (0.00m water depth), which seemed to be a compromise between District projections that minimum water depths in STA-2 cells would be held between 6" above ground and 6" below ground. We also added a provision to PMSAV that shuts off evapotranspiration when water depth decreases below 0.01 m. This tends to impose a lower limits on simulated water depths to slightly above 0.0 m, which may be an artificial limitation, but is necessitated at least until drydown processes in SAV are understood adequately for model formulation.

In terms of wetland hydraulics, we employed the standard TIS model for PMSAV in design mode. We assumed that prominent short-circuiting (such as evidenced in Cell 4) would not be a design feature propagated in future SAV wetlands, so we did not employ the special features described above for the Cell 4 Hydraulics Model. The specific number of TIS for each STSOC simulation was treated as a design variable, dependent upon the number of internal compartments that were assumed. This approach allowed for cost -benefit analyses assessing the tradeoff between purchasing additional land versus constructing structures for internal compartmentalization to achieve effluent TP goals.

In design mode, the PMSAV P-cycling model was identical to the one discussed above. For Post-BMP STSOC simulations, we employed our Post-BMP calibration coefficients. Similarly, for Post-STA simulations, we employed Post-STA coefficients.

Furthermore, STSOC design simulations were conducted assuming steady-state (post-startup) conditions. To simulate steady-state conditions in PMSAV, the design model was run for two iterations, where average values of model storages (biomass, plant-P, sediment-P) from the first iteration were used as initial conditions for the second simulation. This technique effectively eliminates sensitivity of simulated TP values to initial conditions.

*Calibration and Simulation Data Ranges*

It is almost inevitable that issues arise concerning design simulations producing data outside of the range of values in the calibration dataset. It is generally accepted that it is undesirable to extrapolate model predictions outside the range of values in the calibration data set. In applying PMSAV to design simulations, our top priority was to limit the simulation applicability to the effluent TP predictions equal to or above the long-term average effluent concentrations values evident in the NTC-15 and Cell 4 calibration periods.

In design mode, there are two model PMSAV variables that can be adjusted to achieve treatment goals: STA footprint and internal compartmentalization (TIS). The flow-weighted mean effluent concentration during the NTC-15 calibration period was approximately 25 µg/L. Therefore for Post-BMP simulations, we allowed combinations of area and TIS (the 2 design variables) that produced effluent TP concentrations greater than or equal to 25 µg/L. Similarly, the flow-weighted mean effluent concentration during Cell 4 calibration period was approximately 21 µg/L. However for a 2-year period during the calibration period, Cell 4 effluent averaged 14 µg/L. Since this 14 µg/L mean value was calculated from a robust data set (weekly composite samples comprised of 21 grabs/week, which amounts to averaging approximately 2200 grab samples over the 2-year period), we employed a lower limit for Post-STA simulations of 14 µg/L. So, for Post-STA simulations, we allowed combinations of area and TIS that produced effluent TP concentrations greater than or equal to 14 µg/L.

Table 4-7 summarizes the mean and range of values for inflow and outflow TP concentration, hydraulic loading and depth for Post-BMP and Post-STA calibration data sets, as well as for representative simulated data sets. The simulated values in Table 4.7 are provided as an example, and not for design purposes. These values were produced with 3-TIS simulations and with an STA footprint area that produced 25 µg/L and 14 µg/L for Post-BMP and Post-STA simulations respectively. For reference, the Post-BMP simulation required approximately 60% of the STA-2 footprint to achieve 25 µg/L effluent using the Post-BMP STSOC input data set (TIS=3). And the Post-STA simulation required approximately 60% of the STA-2 footprint to achieve 14 µg/L effluent using the Post-STA STSOC input data set (TIS=3).

**Table 4-7.** Comparison of mean and ranges of parameters from calibration data sets and typical STSOC simulations.

| **Parameter** | | **Post-BMP** | | **Post-STA** | |
|---|---|---|---|---|---|
| | | NTC-15 Calibration | STSOC Simulation | Cell 4 Calibration | STSOC Simulation |
| TP – influent (µg/L) | mean | 80 | 122 | 58 | 50 |
| | range | 25 – 170 | 8 – 450 | 17 – 140 | 3 – 184 |
| TP – effluent (µg/L) | mean | 26 | 25 | 21 | 14 |
| | range | 10 – 43 | 10 – 119 | 6 – 64 | 4 – 51 |
| HLR (cm/d) | mean | 13 | 4.0 | 12 | 3.2 |
| | range | 6 – 28 | 0 – 46 | 0 – 49 | 0 – 37 |
| Depth (cm) | mean | 81 | 50 | 73 | 46 |
| | range | 58 – 97 | 9 – 132 | 30 – 100 | 9 – 127 |

Based on the data comparisons in Table 4-7, it is important to note the following:

- The mean influent TP concentration in Post-BMP STSOC simulations exceeds the calibration mean by ~50%. While some of DBE's mesocosm platform evaluations have been conducted with mean influent TP in the range of 100-110 µg/L (similar to the STSOC influent), influent concentrations to both SAV test cell platforms averaged around 80 µg/L.

- The mean HLR in the Post-BMP STSOC simulation is substantially lower than the mean in the NTC-15 calibration dataset (4 cm / d compared to 13 cm / d).
- Similarly, the mean HLR in the Post-STA STSOC is substantially lower than the mean in the Cell 4 calibration dataset (3.2 cm / d compared to 12 cm / d).

Although not evident in Table 4-7, it is also important to note that throughout most of its calibration period, NTC-15 was essentially a steady flow, steady depth evaluation (flows were changed twice). This is notably different than the Cell 4 calibration period, which demonstrated variable flows and depths. However, in comparison to the highly pulsed STSOC simulations, both NTC-15 and Cell 4 calibration datasets (Post-BMP and Post-STA) could be characterized as 'fairly steady'.

Some of these issues raised above represent serious shortcomings in applying these model calibrations to STA design efforts. However, at this point of our Phase II assessment program, these platforms still represent the best available systems for model calibration. Therefore it is essential to interpret our design simulation results with caution and with the awareness that their findings are restricted by limitations in the available calibration data sets.

### 4.2.2 PMSAV and Pulse Loading

*Comparative Analysis of Cell 4 and Post-STA STSOC Pulses*

Figure 4-18 shows a comparison of P-load pulses from Cell 4 data during the Post-STA calibration period and to the Post-STA STSOC data set (50 µg/l flow-weighted inflow concentration). The scatter-plot shows the duration of pulses and mean P-loading during that duration. To produce this data, we used the following definitions of when a "pulse" begins and ends:

- A pulse begins when the daily areal P-loading rate (g / m2 / d) exceeds 1.5x the long-term average P-loading rate in the dataset.
- A pulse ends when the daily areal P-loading rate drops below 1.5x the long-term average P-loading rate for at least two consecutive days.

For the STSOC dataset, it was also necessary to define a footprint area over which the loading rate was calculated. We used an area of 6.8 $km^2$, which is about ¼ of the STA-2 footprint. Using

PMSAV, we estimated that this footprint with the Post-STA STSOC dataset yields a flow-weighted mean effluent concentration of 14 µg/L. As seen in the figure, the Cell 4 pulses and STSOC pulses are comparable. It is also important to consider that the STSOC pulses comprise approximately 82% of the total load in the 9.75-year STSOC record, while the Cell 4 pulses comprise about 59% of total load during the 3.75-year calibration period, suggesting that Cell 4 was more "steadily" loaded than in the STSOC dataset. Taken together, these findings suggest that the principal difference between Cell 4 and STSOC 4 datasets is due not so much to differences in pulse magnitudes and durations, but to the fact that the pulses comprise a more significant fraction of the total load in the STSOC data. It is also important to note that if the assumed STA area in this analysis (15.2 $km^2$) were increased (decreased), the STSOC loading rates in Figure 4-18 would decrease (increase) accordingly.

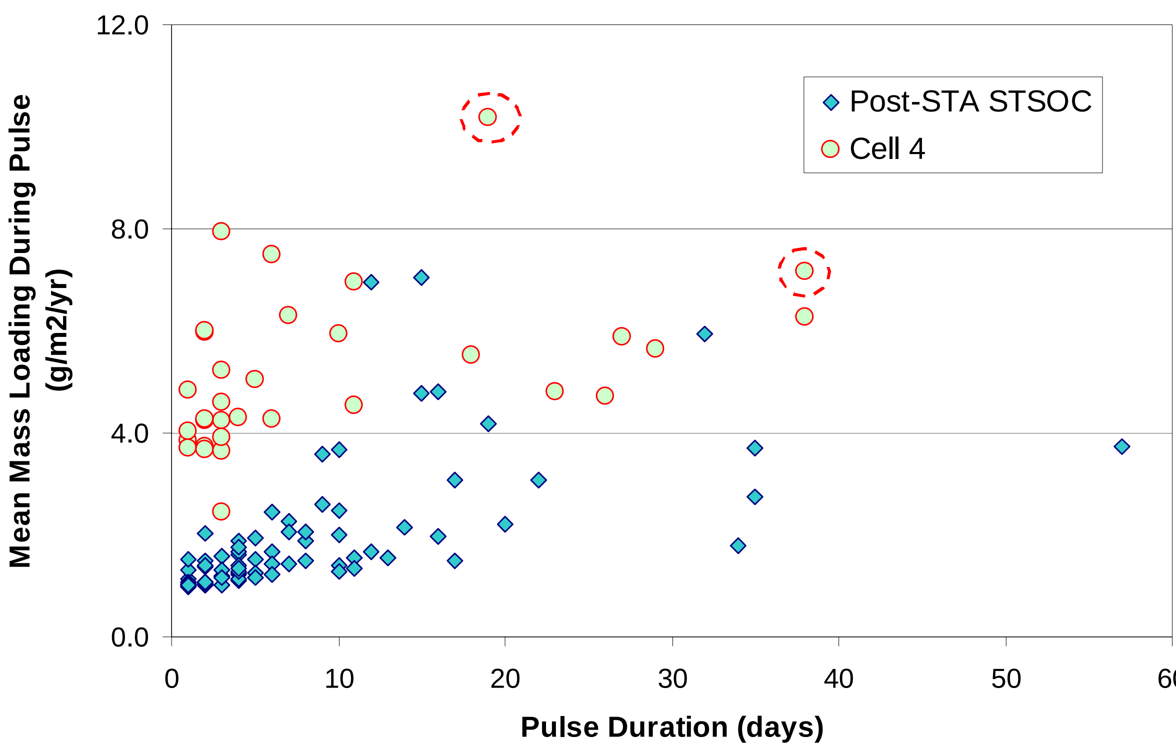



**Figure 4-18.** Comparison of P-load pulses in Cell 4 and Post-STA STSOC datasets. The red circles indicate two "pulses" within the larger Cell 4 October 1999 – January 2000 high load event.

*PMSAV Pulse Response*

Figure 4-19 shows the inflow P-load time history of the same Post-STA STSOC design dataset that was analyzed above (50 ppb flow weighted mean concentration). Three pulses (circled on the larger time history) are shown in greater resolution at the bottom of the figure, along with simulated PMSAV effluent load profiles. Together, these three pulses comprise approximately 24% of the total inflow load in the 9.75-year dataset (here, pulses are defined as beginning when their P-load is greater than 0.0 kg/d and ended when they return to approximately 0.0 kg/d). The PMSAV simulated response shown in the figure was calculated using a 15.2-$km^2$ footprint, which yielded a 14 ppb effluent concentration (flow-weighted mean, TIS=3). The PMSAV simulation predicts approximately 66% TP removal during these three pulses (combined), which is slightly less than the 74% average over the entire simulation period. The average mass removal rate during these three pulses was approximately 2.5 $g/m^2/yr$, which is less than the 4.3 $g/m^2/yr$ removal rate that was demonstrated in Cell 4 during the last quarter of 1999 (3-month average, September-December).

It is important to note that there are no special adjustments to removal coefficients or any other aspect of the PMSAV formulation to accommodate P removal during pulse events. The model predicts elevated mass removal rates with elevated water column TP concentrations (Table 4-4), just as has been demonstrated in numerous mesocosm, test cell, and Cell 4 assessments (DBE, 2002). During pulses, short retention times (due to high HLRs) limit achievable effluent concentrations to values higher than average. During the pulse with the highest magnitude in the Post-STA STSOC dataset (August 1981), the hydraulic retention time dropped to about 1.8-days (using the 6.8-$km^2$ footprint) during the peak inflow (note that larger footprint areas increase HRT). It is important to note that this HRT is greater than 1.5-day HRT used in one of the DBE mesocosm assessments (DBE, 2002), which demonstrated extremely high mass removal rates for extended periods (~8.5 $g/m^2/yr$, 3-year average), but higher effluent concentrations than mesocosms operated at lower loading. The highest effluent concentration in the Post-STA STSOC simulation was 52 ppb. For reference, Cell 4 had several effluent TP values in the 50-60 ppb range in February 2000, which was towards the end of a sequence of several very large P-pulses. We provide additional discussion of Cell 4 pulse effects in Section 4.33.

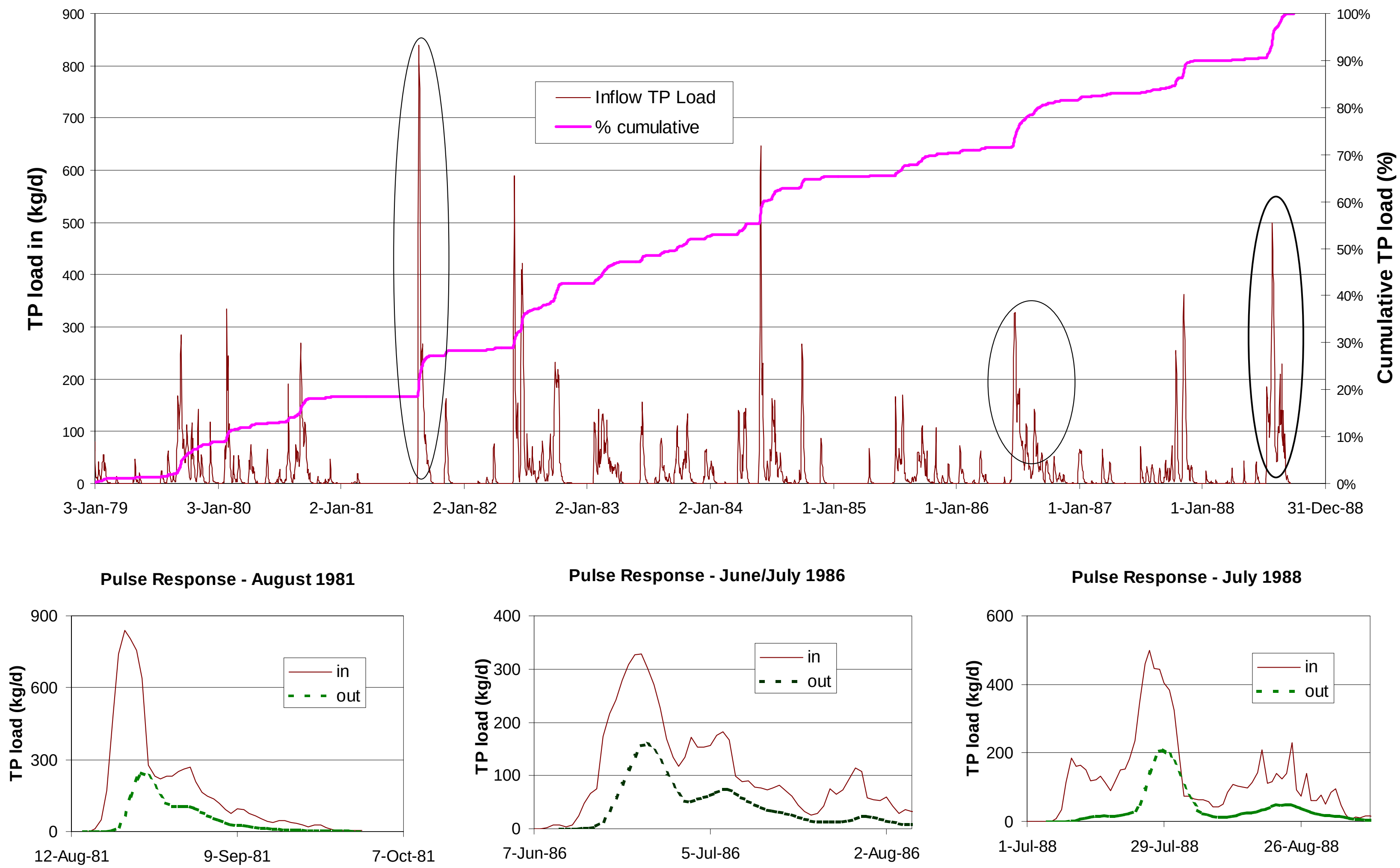



**Figure 4-19.** PMSAV pulse response in a Post-STA STSOC simulation.

### 4.2.3 PMSAV Model Simulations Results

We performed simulations with the PMSAV Design Model for various scenarios to determine required STA footprint areas to meet the Post-BMP and Post-STA outflow TP targets. Table 4-8 summarizes the model simulations that were conducted for this analysis.

**Table 4-8.** Summary of model simulations. Post-BMP simulations assume an inflow TP level of 122, which is reduced to either 26 or 20 µg/L. Post-STA simulations start with inflow values of 50, 40, 30 and 25 µg/L. Outflow TP values of 20 and 14 µg/L are simulted for each inflow value.

| Data Set | $P_{in}$ (µg/L) | $P_{out}$ (µg/L) | Bypass (%) | No. Tanks-In-Series (TIS) |
|---|---|---|---|---|
| Post BMP | 122 | 20 | 0, 10, 20 | 1-20 |
| | | 26 | | |
| Post STA | 50 | 14 | | |
| | 40 | | | |
| | 30 | | | |
| | 25 | | | |
| | 50 | 20 | | |
| | 40 | | | |
| | 30 | | | |
| | 25 | | | |

For most of the model runs, we utilized a "conceptualized" footprint that was established to have an identical area to STA-2. For this conceptualized STA-2 footprint, we held the wetland width to a constant value of 5,591 m to simplify the computations (note that the actual STA-2 width is variable). This value was determined by dividing the actual STA-2 area of 6,430 acres by the length of Cell 3 (app. 4,600 m) to get a uniform width of 5,591 m.

The methodology used in performing the model simulations was to change the "area" term in the model by multiplying by a minimum factor of 0.01 until the desired $P_{out}$ concentration for the particular run was achieved. When the $P_{out}$ concentration was achieved for a certain number of TIS for the particular inflow and outflow concentration scenario, the number of TIS was increased by one and the "area" term was once again changed until the outflow concentration target was met. This process was repeated for each number of TIS until there was no change in the required footprint area between subsequent runs. The final simulation for each condition was performed with the number of TIS set to the maximum of 20.

A synopsis of model simulation results for Post-BMP footprint sizing is provided in Table 4-9. Post-BMP area requirements were determined for flow-weighted outflow TP concentrations of 26 and 20 µg/L (based on inflow concentrations of 122 µg/L), with three flow bypass scenarios (0%, 10% and 20% of flow). The model simulations demonstrate that the area requirement of a SAV wetland used for Post-BMP treatment is sensitive to both the hydraulic efficiency (number of TIS), and to the percentage of flow bypassed.

The sensitivity of SAV wetland area requirements to hydraulic efficiency is particularly important, and is depicted in Figures 4-20 and 4-21. Note, for example, that to achieve an outflow concentration of 26 µg/L under 0% bypass conditions, the area requirement is approximately 7,500 acres when a hydraulic efficiency of 1 TIS is assumed. When the SAV wetland is modeled as a 5 TIS system, the area requirement is more than halved (Figure 4-21). Our previous tracer studies have shown that SAV wetlands, with no internal compartmentalization, can exhibit hydraulic efficiencies ranging from 3 TIS (test cells) to 1.3 TIS (Cell 4, with its obvious hydraulic short circuits). Because of this strong sensitivity of SAV performance to hydraulic characteristics, for conceptual design purposes we evaluated costs of Post-BMP wetland for several hydraulic efficiency (TIS) scenarios.

**Table 4-9.** Area requirements for a Post-BMP SAV treatment wetland as a function of hydraulic performance (number of tanks-in-series) and flow bypass percentage.

## PMSAV Conceptual Design

STA2 Footprint

| | | |
|---|---|---|
| Area | 6430 | ac |
| Width | 5591 | m |
| Length | variable | m |

**Post BMP Model Run Results**

| | | $P_{out}$ = 20 ppb | | | | | | | $P_{out}$ = 26 ppb | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | |
| Bypass % | # T.I.S. | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb |
| 0% | 1 | 8602 | 5591 | 149581 | 4.81E+07 | 12025 | 22597 | 49826 | 5428 | 5591 | 107925 | 3.03E+07 | 7575 | 20934 | 46159 |
| | 2 | 4508 | | 95851 | 2.52E+07 | 6300 | 21987 | 48481 | 3128 | | 77740 | 1.75E+07 | 4375 | 20587 | 45394 |
| | 3 | 3634 | | 84381 | 2.03E+07 | 5075 | 21883 | 48252 | 2622 | | 71099 | 1.47E+07 | 3675 | 20560 | 45335 |
| | 4 | 3266 | | 79551 | 1.83E+07 | 4575 | 21851 | 48181 | 2392 | | 68081 | 1.34E+07 | 3350 | 20542 | 45295 |
| | 5 | 3082 | | 77136 | 1.72E+07 | 4300 | 21862 | 48206 | 2254 | | 66270 | 1.26E+07 | 3150 | 20513 | 45231 |
| | 6 | 2944 | | 75325 | 1.65E+07 | 4125 | 21846 | 48170 | 2208 | | 65666 | 1.23E+07 | 3075 | 20586 | 45392 |
| | 7 | 2898 | | 74721 | 1.62E+07 | 4050 | 21905 | 48301 | 2162 | | 65062 | 1.21E+07 | 3025 | 20610 | 45445 |
| | 8 | 2852 | | 74118 | 1.59E+07 | 3975 | 21936 | 48369 | 2116 | | 64459 | 1.18E+07 | 2950 | 20602 | 45427 |
| | 9 | 2760 | | 72910 | 1.54E+07 | 3850 | 21878 | 48241 | 2070 | | 63855 | 1.16E+07 | 2900 | 20569 | 45355 |
| | 10 | 2714 | | 72307 | 1.52E+07 | 3800 | 21872 | 48228 | 2070 | | 63855 | 1.16E+07 | 2900 | 20631 | 45491 |
| | 11 | 2714 | | 72307 | 1.52E+07 | 3800 | 21926 | 48347 | | | | | | | |
| | 20 | 2714 | | 72307 | 1.52E+07 | 3800 | 22217 | 48988 | 2070 | | 63855 | 1.16E+07 | 2900 | 20934 | 46159 |
| 10% | 1 | 6624 | 5591 | 123622 | 3.70E+07 | 6624 | 19195 | 42325 | 4048 | 5591 | 89814 | 2.26E+07 | 5650 | 17740 | 39117 |
| | 2 | 3358 | | 80759 | 1.88E+07 | 4700 | 18700 | 41234 | 2300 | | 66873 | 1.29E+07 | 3225 | 17449 | 38475 |
| | 3 | 2714 | | 72307 | 1.52E+07 | 3800 | 18648 | 41119 | 1932 | | 62044 | 1.08E+07 | 2700 | 17448 | 38473 |
| | 4 | 2438 | | 68684 | 1.36E+07 | 3400 | 18632 | 41084 | 1748 | | 59629 | 9.77E+06 | 2443 | 17401 | 38369 |
| | 5 | 2300 | | 66873 | 1.29E+07 | 3225 | 18648 | 41119 | 1702 | | 59025 | 9.52E+06 | 2380 | 17511 | 38612 |
| | 6 | 2208 | | 65666 | 1.23E+07 | 3075 | 18654 | 41132 | 1610 | | 57818 | 9.00E+06 | 2250 | 17427 | 38427 |
| | 7 | 2116 | | 64459 | 1.18E+07 | 2950 | 18613 | 41042 | 1610 | | 57818 | 9.00E+06 | 2250 | 17536 | 38667 |
| | 8 | 2070 | | 63855 | 1.16E+07 | 2900 | 18618 | 41053 | | | | | | | |
| | 9 | 2070 | | 63855 | 1.16E+07 | 2900 | 18685 | 41200 | | | | | | | |
| | 20 | 1978 | | 62647 | 1.11E+07 | 2775 | 18852 | 41569 | 1564 | | 57214 | 8.74E+06 | 2185 | 17849 | 39357 |
| 20% | 1 | 5474 | 5591 | 108529 | 3.06E+07 | 7650 | 16637 | 36685 | 3312 | 5591 | 80155 | 1.85E+07 | 4625 | 15363 | 33875 |
| | 2 | 2760 | | 72910 | 1.54E+07 | 3850 | 16248 | 35827 | 1886 | | 61440 | 1.05E+07 | 2625 | 15159 | 33426 |
| | 3 | 2208 | | 65666 | 1.23E+07 | 3075 | 16189 | 35697 | 1564 | | 57214 | 8.74E+06 | 2185 | 15125 | 33351 |
| | 4 | 1978 | | 62647 | 1.11E+07 | 2775 | 16172 | 35659 | 1426 | | 55403 | 7.97E+06 | 1993 | 15112 | 33322 |
| | 5 | 1886 | | 61440 | 1.05E+07 | 2625 | 16219 | 35763 | 1380 | | 54799 | 7.72E+06 | 1930 | 15185 | 33483 |
| | 6 | 1794 | | 60233 | 1.00E+07 | 2500 | 16197 | 35714 | 1334 | | 54196 | 7.46E+06 | 1865 | 15190 | 33494 |
| | 7 | 1748 | | 59629 | 9.77E+06 | 2443 | 16212 | 35747 | 1288 | | 53592 | 7.20E+06 | 1800 | 15148 | 33401 |
| | 8 | 1702 | | 59025 | 9.52E+06 | 2380 | 16201 | 35723 | 1288 | | 53592 | 7.20E+06 | 1800 | 15223 | 33567 |
| | 9 | 1702 | | 59025 | 9.52E+06 | 2380 | 16275 | 35886 | | | | | | | |
| | 20 | 1656 | | 58421 | 9.26E+06 | 2315 | 16448 | 36268 | 1288 | | 53592 | 7.20E+06 | 1800 | 15498 | 34173 |

[1] Includes 2 existing interior levees equal to "length"

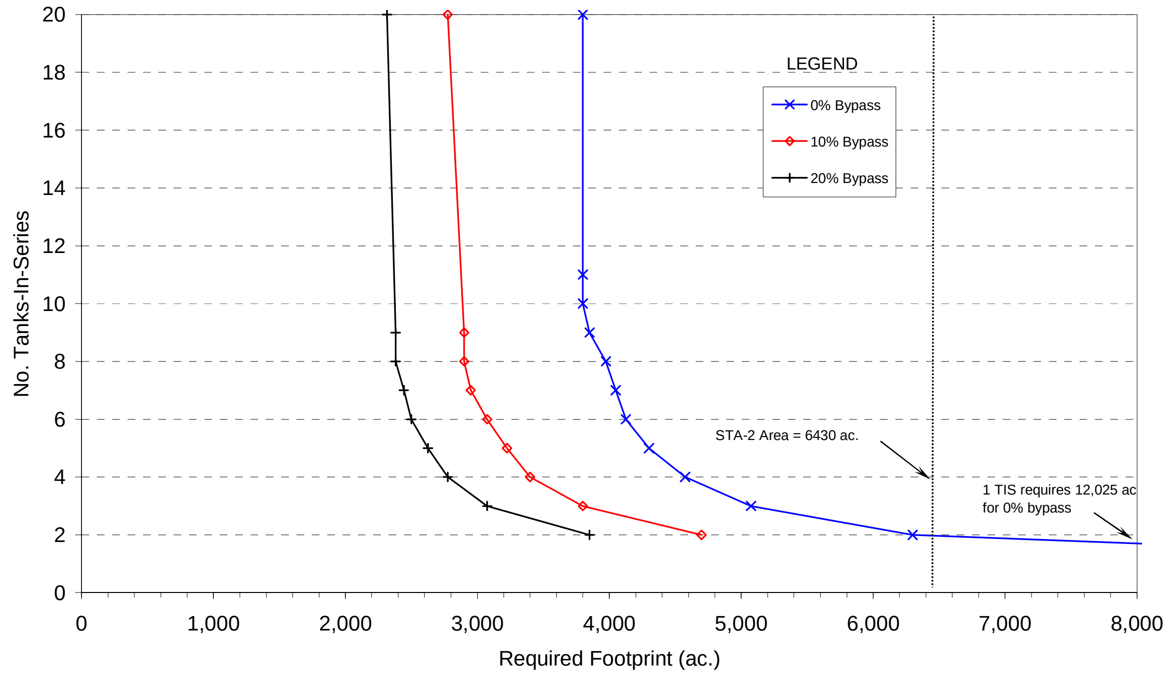



**Figure 4-20.** Predicted relationship between flow bypass, hydraulic performance (expressed as tanks-in-series) and Post-BMP SAV wetland footprint. Target outflow TP concentration is 20 µg/L.

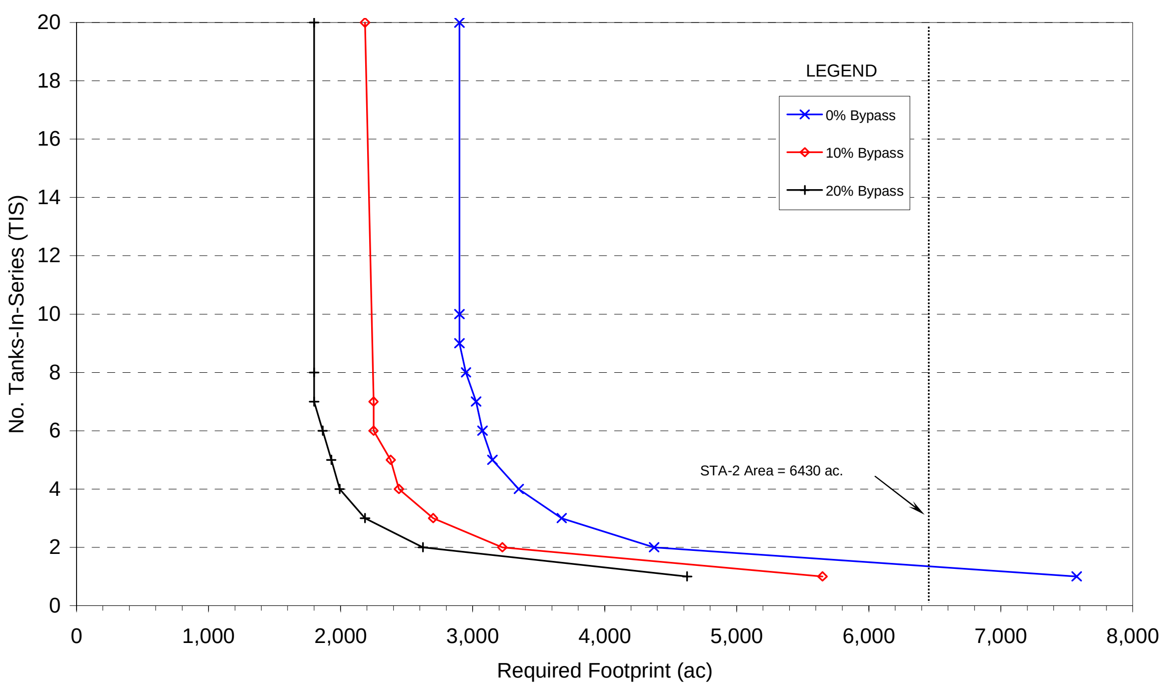



**Figure 4-21.** Predicted relationship between flow bypass, hydraulic performance (expressed as tank-in-series) and Post-BMP SAV wetland footprint. Target outflow TP concentration is 26 µg/L.

As part of this effort, we developed an “optimum” conceptual design analysis, in which we assumed that we can deploy a full-scale Post-BMP SAV wetland that will have good hydraulic efficiency, approximating 5 TIS. This is achieved by filling existing farm canals that lie parallel to flow, and installing five limerock level spreaders (details below) within the footprint, perpendicular to flow. Fill for the parallel farm canals is obtained on-site, by excavating shallow ditches perpendicular to flow. Under this scenario, the Post-BMP area requirement for an SAV wetland to reduce TP concentrations from 122 to 26 µg/L, with 0% bypass, is 3,150 acres. This area requirement is slightly less than one-half the STA-2 footprint.

We also assessed other design scenarios where the Post-BMP SAV wetlands have reduced hydraulic efficiencies (TIS of 1 and 2). The TIS of 1 would be a hydraulic performance slightly worse than that exhibited by Cell 4, and would entail leaving in place (and possibly expanding) farm and levee canals that lie parallel to flow. Under this scenario, the Post-BMP area requirement for an SAV wetland to reduce TP concentrations from 122 to 26 µg/L, with 0% bypass, is 7,575acres. This area requirement is about 15% greater than the existing STA-2 footprint. The Post-BMP SAV wetland footprint under the TIS=2 scenario, a hydraulic efficiency comparable of that of NTC-15, would be substantially smaller, at 4,375 acres.

Results for model simulations of area requirements for an SAV wetland for Post-STA treatment are shown in Table 4-10. Post-STA area requirements were determined for flow-weighted outflow TP concentrations of 20 and 14 µg/L (based on inflow concentrations of 50, 40, 30 and 25 µg/L), with three flow bypass scenarios (0%, 10% and 20% of flow). The model simulations demonstrate that the area requirement of a SAV wetland used for Post-STA treatment is sensitive to the hydraulic efficiency (number of TIS), the percentage of flow bypassed, and, of course, the starting inflow concentration (Figure 4-22).

**Table 4-10.** Area requirements for a Post-STA SAV treatment wetland as a function of hydraulic performance (number of tanks-in-series) and flow bypass percentage.

## PMSAV Conceptual Design

STA2 Footprint

| | | |
|---|---|---|
| Area | 6430 | ac |
| Width | 5591 | m |
| Length | variable | m |

**Post STA Model Run Results**

| | | | $P_{in}$ = 50 ppb | | | | | | | $P_{in}$ = 25 ppb | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | |
| Bypass % | $P_{out}$ | # T.I.S. | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb |
| 0 | 14 ppb | 1 | 5336 | 5591 | 105044 | 2.98E+07 | 7450 | 7318 | 16136 | 1656 | 5591 | 56748 | 9.26E+06 | 2315 | 2196 | 4842 |
| | | 2 | 3174 | | 76670 | 1.77E+07 | 4425 | 7014 | 15466 | 1242 | | 51315 | 6.94E+06 | 1735 | 2133 | 4703 |
| | | 3 | 2668 | | 70030 | 1.49E+07 | 3725 | 6940 | 15303 | 1150 | | 50107 | 6.43E+06 | 1608 | 2132 | 4701 |
| | | 4 | 2438 | | 67011 | 1.36E+07 | 3400 | 6903 | 15221 | 1104 | | 49504 | 6.17E+06 | 1543 | 2127 | 4690 |
| | | 5 | 2346 | | 65804 | 1.31E+07 | 3275 | 6907 | 15230 | 1058 | | 48900 | 5.92E+06 | 1480 | 2103 | 4637 |
| | | 6 | 2254 | | 64596 | 1.26E+07 | 3150 | 6883 | 15177 | 1058 | | 48900 | 5.92E+06 | 1480 | 2116 | 4666 |
| | | 7 | 2208 | | 63993 | 1.23E+07 | 3075 | 6880 | 15170 | | | | | | | |
| | | 8 | 2162 | | 63389 | 1.21E+07 | 3025 | 6866 | 15140 | | | | | | | |
| | | 9 | 2162 | | 63389 | 1.21E+07 | 3025 | 6885 | 15181 | | | | | | | |
| | | 20 | 2116 | | 62785 | 1.18E+07 | 2950 | 6906 | 15228 | 1104 | | 49504 | 6.17E+06 | 1543 | 2149 | 4739 |
| 10 | 14 ppb | 1 | 3864 | 5591 | 85726 | 2.16E+07 | 5400 | 6198 | 13667 | 1150 | 5591 | 50107 | 6.43E+06 | 1608 | 1791 | 3949 |
| | | 2 | 2254 | | 64596 | 1.26E+07 | 3150 | 5960 | 13142 | 874 | | 46485 | 4.89E+06 | 1223 | 1747 | 3852 |
| | | 3 | 1886 | | 59767 | 1.05E+07 | 2625 | 5907 | 13025 | 828 | | 45882 | 4.63E+06 | 1158 | 1762 | 3885 |
| | | 4 | 1748 | | 57956 | 9.77E+06 | 2443 | 5901 | 13012 | 782 | | 45278 | 4.37E+06 | 1093 | 1740 | 3837 |
| | | 5 | 1656 | | 56748 | 9.26E+06 | 2315 | 5882 | 12970 | 782 | | 45278 | 4.37E+06 | 1093 | 1755 | 3870 |
| | | 6 | 1610 | | 56144 | 9.00E+06 | 2250 | 5881 | 12968 | | | | | | | |
| | | 7 | 1564 | | 55541 | 8.74E+06 | 2185 | 5864 | 12930 | | | | | | | |
| | | 8 | 1564 | | 55541 | 8.74E+06 | 2185 | 5886 | 12979 | | | | | | | |
| | | 20 | 1518 | | 54937 | 8.49E+06 | 2123 | 5888 | 12983 | 828 | | 45882 | 4.63E+06 | 1158 | 1776 | 3916 |
| 20 | 14 ppb | 1 | 3036 | 5591 | 74859 | 1.70E+07 | 4250 | 5349 | 11795 | 874 | 5591 | 46485 | 4.89E+06 | 1223 | 1509 | 3327 |
| | | 2 | 1794 | | 58559 | 1.00E+07 | 2500 | 5184 | 11431 | 690 | | 44070 | 3.86E+06 | 965 | 1496 | 3299 |
| | | 3 | 1472 | | 54333 | 8.23E+06 | 2058 | 5119 | 11287 | 644 | | 43467 | 3.60E+06 | 900 | 1496 | 3299 |
| | | 4 | 1380 | | 53126 | 7.72E+06 | 1930 | 5131 | 11314 | 644 | | 43467 | 3.60E+06 | 900 | 1519 | 3349 |
| | | 5 | 1288 | | 51919 | 7.20E+06 | 1800 | 5094 | 11232 | | | | | | | |
| | | 6 | 1288 | | 51919 | 7.20E+06 | 1800 | 5133 | 11318 | | | | | | | |
| | | 7 | 1242 | | 51315 | 6.94E+06 | 1735 | 5107 | 11261 | | | | | | | |
| | | 20 | 1196 | | 50711 | 6.69E+06 | 1673 | 5096 | 11237 | 690 | | 44070 | 3.86E+06 | 965 | 1538 | 3391 |

| | | | $P_{in}$ = 50 ppb | | | | | | | $P_{in}$ = 25 ppb | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | | Length | Width | Perimeter[1] | Req. STA Area | | P Removed | |
| Bypass % | $P_{out}$ | # T.I.S. | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb | (m) | (m) | (ft) | ($m^2$) | (ac.) | kg | lb |
| 0 | 20 ppb | 1 | 2254 | 5591 | 64596 | 1.26E+07 | 3150 | 5813 | 12818 | 322 | 5591 | 39241 | 1.80E+06 | 450 | 948 | 2090 |
| | | 2 | 1564 | | 55541 | 8.74E+06 | 2185 | 5738 | 12652 | 276 | | 38637 | 1.54E+06 | 385 | 919 | 2026 |
| | | 3 | 1380 | | 53126 | 7.72E+06 | 1930 | 5719 | 12610 | 276 | | 38637 | 1.54E+06 | 385 | 932 | 2055 |
| | | 4 | 1288 | | 51919 | 7.20E+06 | 1800 | 5693 | 12553 | | | | | | | |
| | | 5 | 1242 | | 51315 | 6.94E+06 | 1735 | 5684 | 12533 | | | | | | | |
| | | 6 | 1196 | | 50711 | 6.69E+06 | 1673 | 5647 | 12452 | | | | | | | |
| | | 7 | 1196 | | 50711 | 6.69E+06 | 1673 | 5673 | 12509 | | | | | | | |
| | | 20 | 1196 | | 50711 | 6.69E+06 | 1673 | 5689 | 12544 | 276 | | 38637 | 1.54E+06 | 385 | n/a | |
| 10 | 20 ppb | 1 | 1610 | 5591 | 56144 | 9.00E+06 | 2250 | 4917 | 10842 | 184 | 5591 | 37430 | 1.03E+06 | 258 | 655 | 1444 |
| | | 2 | 1104 | | 49504 | 6.17E+06 | 1543 | 4846 | 10685 | 184 | | 37430 | 1.03E+06 | 258 | 688 | 1517 |
| | | 3 | 966 | | 47693 | 5.40E+06 | 1350 | 4809 | 10604 | | | | | | | |
| | | 4 | 920 | | 47089 | 5.14E+06 | 1285 | 4816 | 10619 | | | | | | | |
| | | 5 | 874 | | 46485 | 5.14E+06 | 1285 | 4775 | 10529 | | | | | | | |
| | | 6 | 874 | | 46485 | 4.89E+06 | 1223 | 4806 | 10597 | | | | | | | |
| | | 20 | 920 | | 47089 | 4.89E+06 | 1223 | 4894 | 10791 | | | | | | | |
| 20 | 20 ppb | 1 | 1242 | 5591 | 51315 | 6.94E+06 | 1735 | 4224 | 9314 | 138 | 5591 | 36826 | 7.72E+05 | 193 | 532 | 1173 |
| | | 2 | 874 | | 46485 | 4.89E+06 | 1223 | 4204 | 9270 | 138 | | 36826 | 7.72E+05 | 193 | 551 | 1215 |
| | | 3 | 782 | | 45278 | 4.37E+06 | 1093 | 4204 | 9270 | | | | | | | |
| | | 4 | 736 | | 44674 | 4.12E+06 | 1030 | 4190 | 9239 | | | | | | | |
| | | 5 | 690 | | 44070 | 3.86E+06 | 965 | 4129 | 9104 | | | | | | | |
| | | 20 | 736 | | 44674 | 4.12E+06 | 1030 | 4207 | 9276 | | | | | | | |

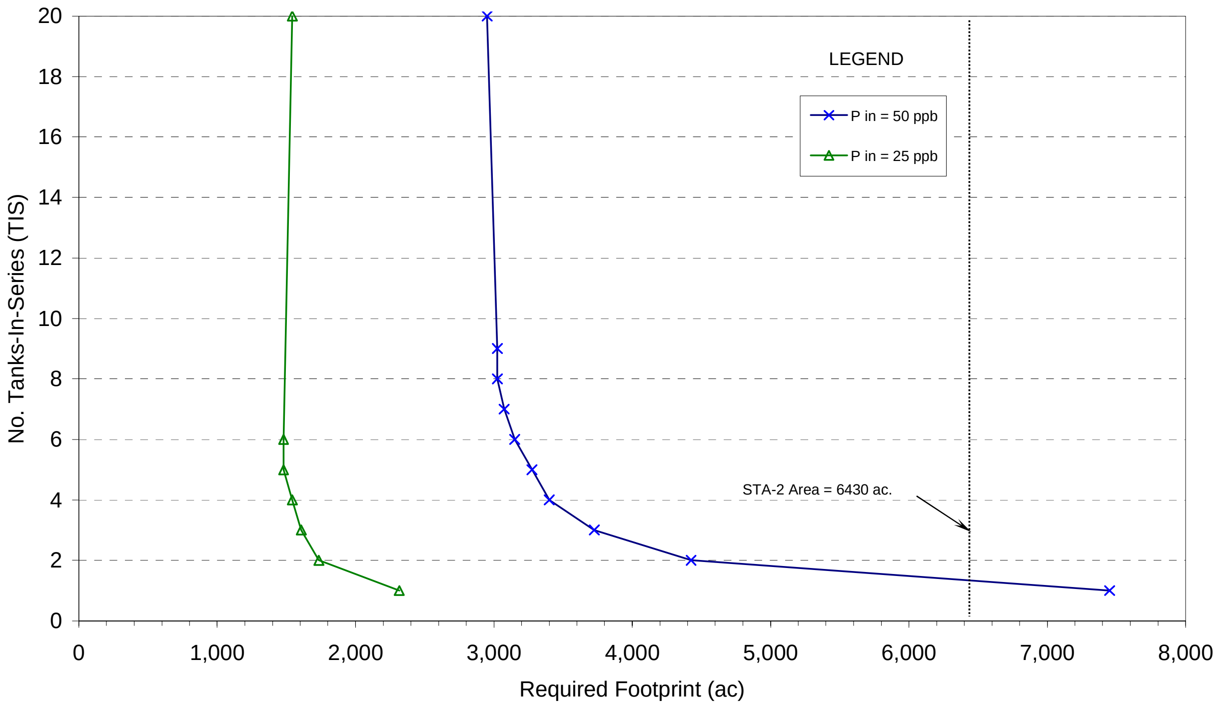



**Figure 4-22.** Predicted relationship between inflow TP concentration, hydraulic performance (expressed as no. tanks-in-series) and Post-STA wetland footprint. Analyses assume a 0% flow bypass.

As with the Post-BMP analysis, we evaluated footprint requirements for Post-STA SAV treatment wetlands that exhibit poor hydraulic efficiency, specifically 1 TIS. Under this scenario, the Post-STA area requirement for an SAV wetland to reduce TP concentrations from 25 to 14 µg/L, with 0% bypass, is 2,315 acres. Post-STA footprints also were calculated assuming an inflow TP concentration of 50 µg/L, and outflow concentrations of 20 and 14 µg/L.

In a more optimum design scenario, we assumed that we can deploy a full-scale SAV wetland for Post-STA treatment that will have a hydraulic efficiency of 2 TIS. This is achieved by filling existing farm canals that lie parallel to flow, and installing one limerock level spreader (details below) within the footprint, perpendicular to flow. Fill for the parallel farm canals is obtained on-site, by excavating shallow canals perpendicular to flow. Under this scenario, the Post-STA area requirement for an SAV wetland to reduce TP concentrations from 25 to 14 µg/L, with 0% bypass, is 1,735 acres.

For this STSOC analysis, we were tasked with promulgating full-scale conceptual STA designs based solely on the SAV/LR technology. The specific Post-BMP and Post-STA designs are provided in the next section. We also developed an optimum design, where the entire SAV wetland is using to remove P from 122 to 14 µg/L. With this assumption, the Post-STA SAV/LR system therefore needs to be situated at the back-end of the Post-BMP SAV/LR wetland. Because a 26 µg/L outflow TP concentration is readily achieved by the Post-BMP SAV wetland, we selected 25 µg/L (from inflow choices of 50, 40, 30 and 25 µg/L) as a logical concentration to use as the inflow for the optimum design of the Post-STA SAV/LR wetland.

For the optimum design, combining the hydraulically-efficient Post-BMP (TIS = 5) and Post-STA (TIS = 2) SAV/LR area requirements results in an overall STA footprint of 4,885 acres. Even assuming a lesser degree of hydraulic efficiency (2 TIS each for Post-BMP and Post-STA wetlands), the total area requirement is 6,110 acres, with both wetlands fitting within the current STA-2 footprint.

## 4.3 SAV/LR Conceptual Design

### 4.3.1 STSOC Conceptual Design

In accordance with STSOC guidelines, we developed a design for a Post-BMP SAV wetland, which essentially "scales-up" the performance observed in NTC-15 during the calibration period. For this analysis, we use inflow and outflow TP concentrations of 122 and 26 µg/L, respectively. NTC-15 exhibited a moderate level of hydraulic efficiency during this period, so we use a TIS value of 2 for this analysis. In this Post-BMP design, the wetland requires 4,375 acres, and therefore fits within the STA-2 footprint (Figure 4-23).

We also developed a STSOC Post-STA design to facilitate comparison to the other advanced technologies. The inflow and outflow values used for this analysis, 50 and 20 µg/L, respectively, are comparable to the mean values observed for Cell 4 during its verification period in December 2001. For this analysis, we assumed extremely poor hydraulic efficiency, attributing a TIS value of 1 to the wetland. Note that the poor hydraulic efficiency (TIS = 1.3) previously exhibited by Cell 4 is due to the presence of farm and levee canals that lie parallel to flow. This STSOC design therefore assumes that such canals would exist, and convey greater than 40% of the flow from inflow to outflow regions of the Post-STA wetland. This Post-STA wetland is designed to fit outside the STA-2 footprint (Figure 4-24), and requires 3,150 acres.

### 4.3.2 Optimum Conceptual Design

Our Phase II field observations demonstrate that physical structures in the STAs that concentrate flows, such as levee canals, farm canals, and large levee culverts, can have an adverse impact on hydraulic performance of the STA wetlands. Highly concentrated flows, such as where G254 inflow culverts are directly in line with relic farm canals, can even scour submerged vegetation and associated unconsolidated sediments. Once these short-circuit pathways are established, they may persist indefinitely.

As a guiding principal for design of internal hydraulic optimization features, we strongly advise against deploying any physical structures that concentrate flows. We believe that conventional berm/culvert designs (such as the G254 levee) may hinder performance due to the adverse effects of flow concentration (and resulting scour /short-circuit zones). We therefore advocate a different approach to hydraulic optimization, focusing on techniques that effectively spread flows and dissipate flow energies, rather than concentrating them.

We prepared a schematic of a conceptual design of full-scale, “hydraulically-optimized” SAV/LR wetland, that incorporates both Post-BMP and Post-STA wetlands in the STA-2 footprint (Figure 4-25). Area within the STA footprint that the model suggests is not “required” by the SAV/LR system for treatment is designated a surplus, “pre-treatment” area. This area likely will be colonized by floating, emergent and submerged macrophytes, and can reduce some of the labile P loading (and dampen hydraulic loadings) to the downstream SAV communities. A typical cross-section of this SAV wetland design is provided in Figure 4-26. A summary of pertinent design and performance factors for the conceptual design is provided in Table 4-11.

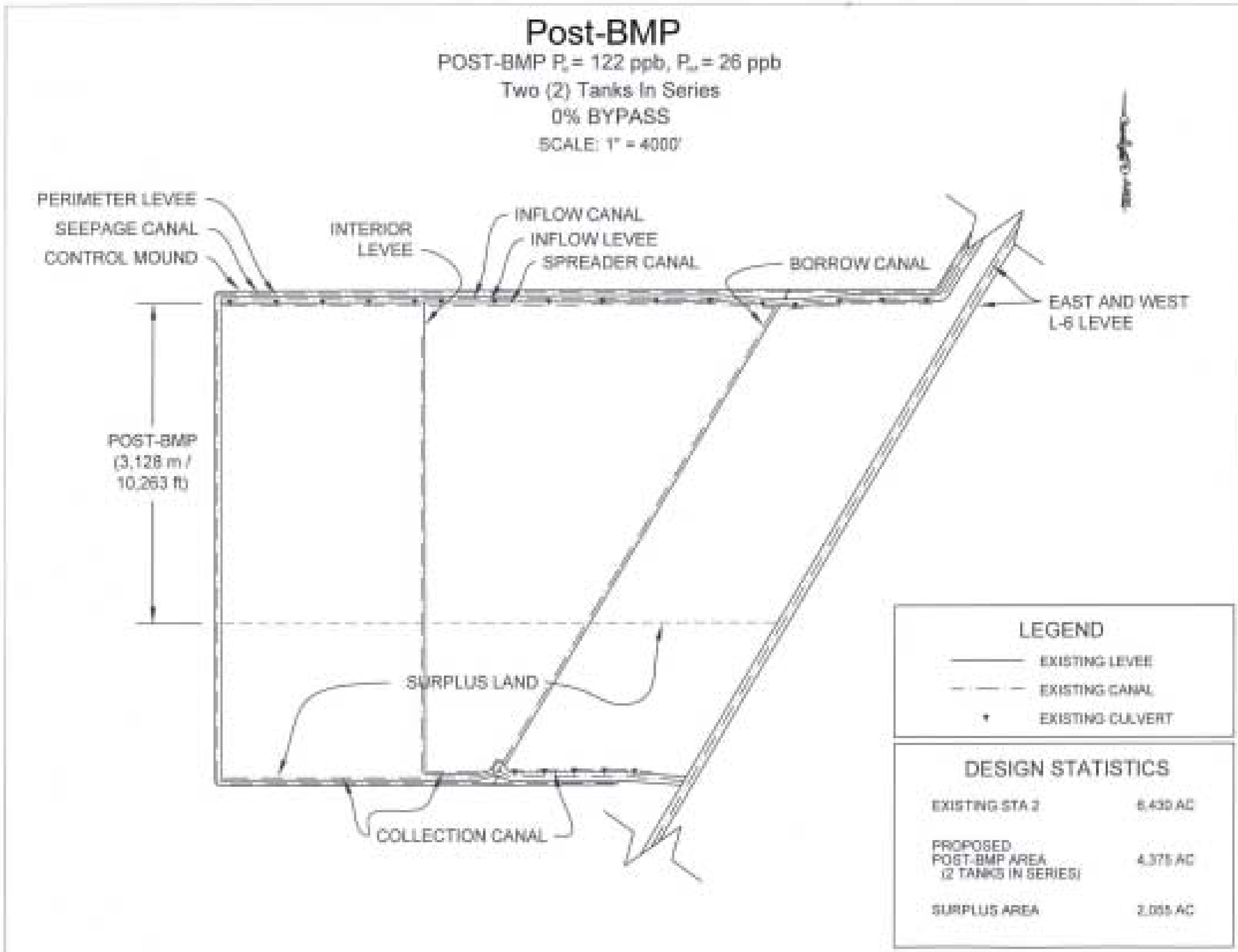



**Figure 4-23.** Schematic of STSOC Post-BMP conceptual design of a full-scale SAV wetland wetland with 0% flow bypass.

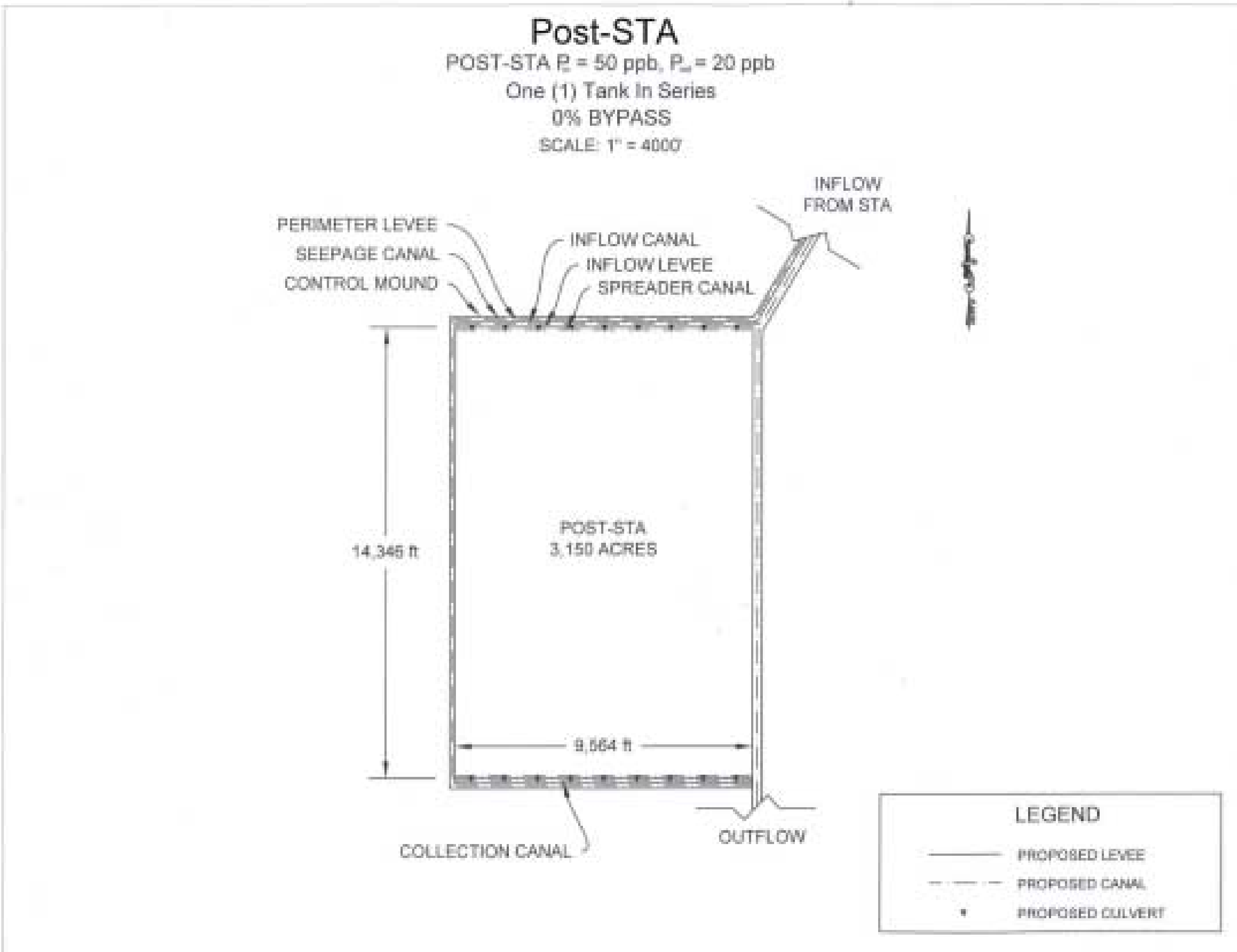



**Figure 4-24.** Schematic of STSOC Post-STA conceptual design of a full-scale SAV wetland with 0% flow bypass.

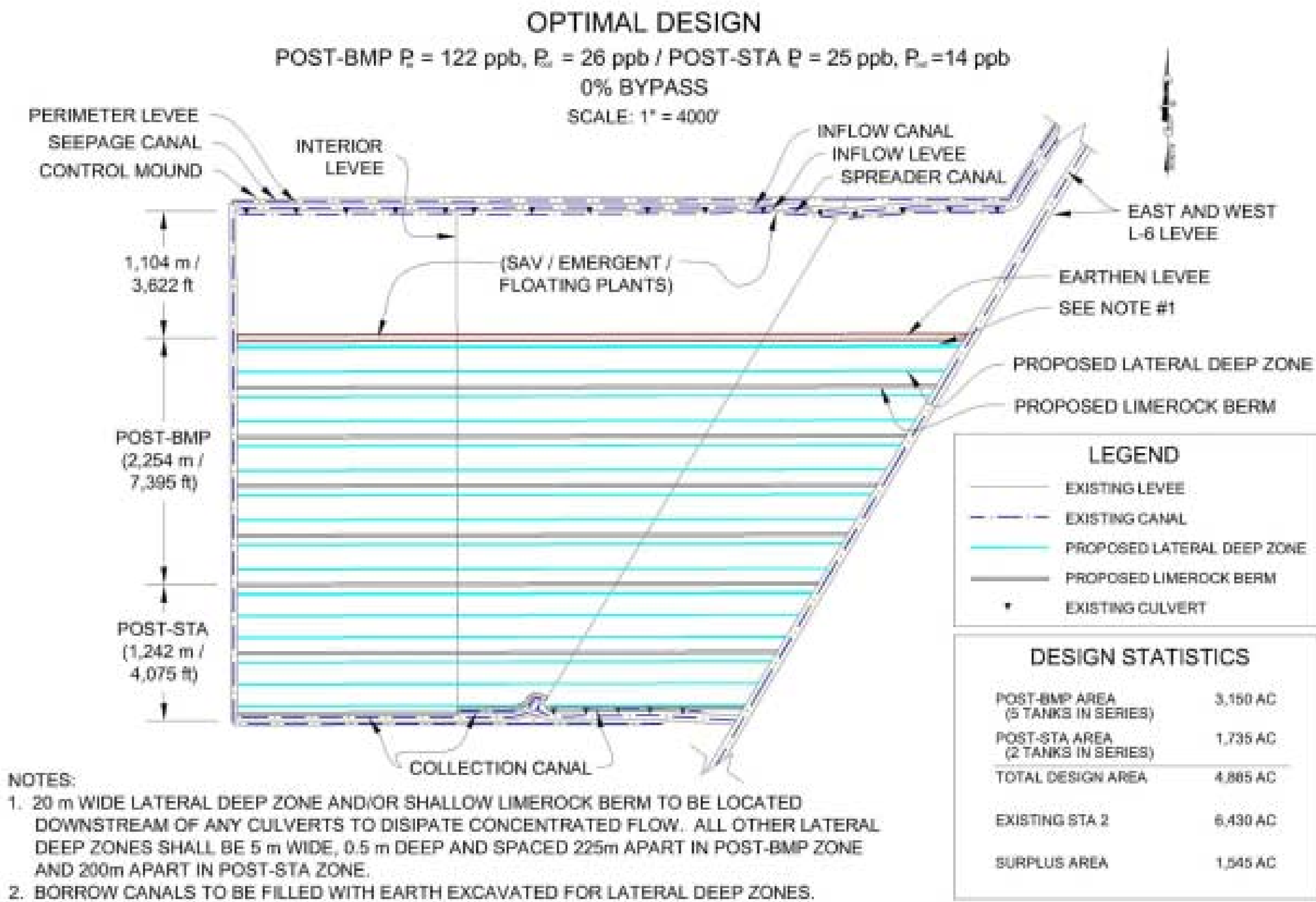



**Figure 4-25.** Schematic of the optimum conceptual design of a full-scale, hydraulically-optimized SAV/LR wetland with 0% flow bypass.

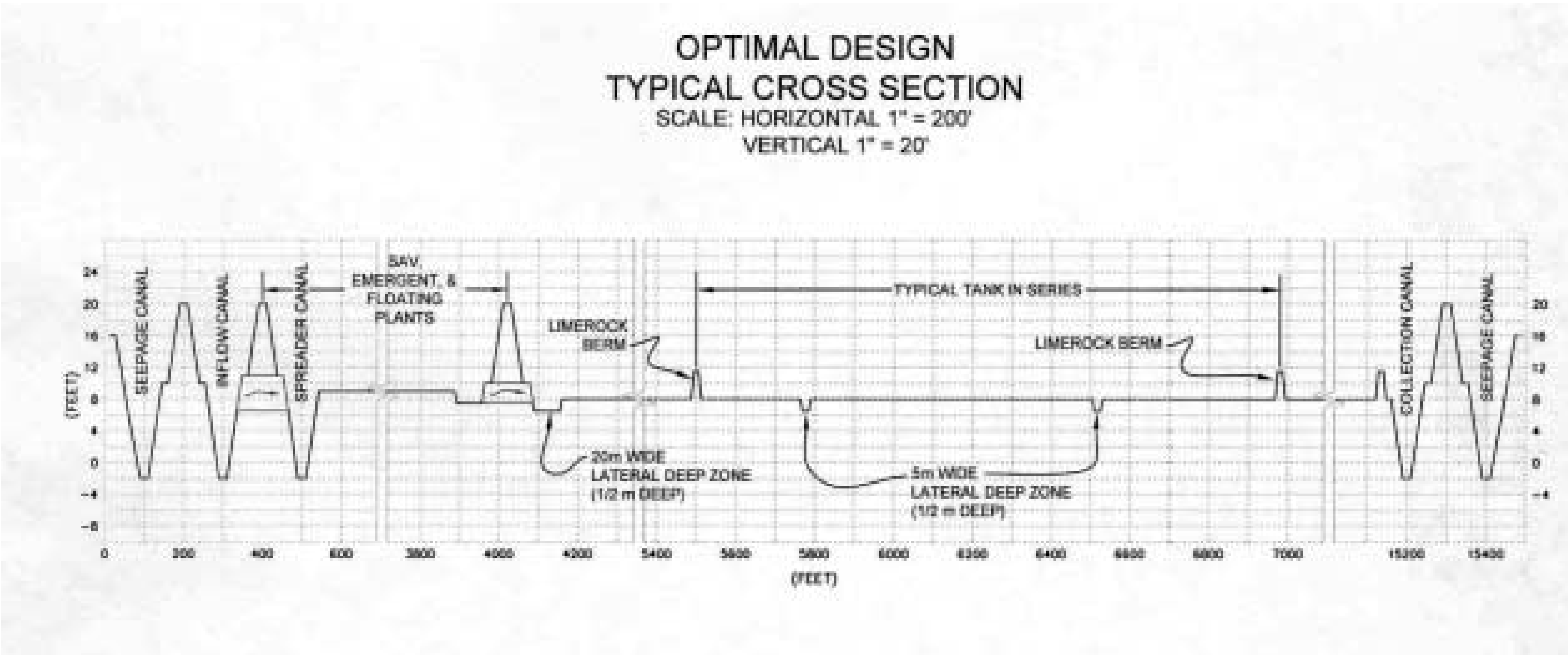



**Figure 4-26.** A typical cross-section of the optimum conceptual SAV wetland design.

**Table 4-11.** Summary of design and performance factors for the SAV/LR wetland.

**Optimum Design**
**Post BMP $P_{out}$ = 26 ppb**
**Post STA $P_{in}$ = 25 ppb, $P_{out}$ = 14 ppb**
**TIS = 7**

**Summary of PMSAV Performance**

| | | Post BMP | | | Post STA | | |
|---|---|---|---|---|---|---|---|
| | | Bypass | | | Bypass | | |
| Parameter | Value | 0 | 10 | 20 | 0 | 10 | 20 |
| $Q_{in}$ ($m^3$/d) | Avg | 613,000 | 551,000 | 490,000 | 530,000 | 477,000 | 424,000 |
| | Max | 7,138,246 | 3,750,000 | 2,820,000 | 6,251,700 | 2,720,000 | 1,915,000 |
| | Min | 0 | 0 | 0 | 0 | 0 | 0 |
| $TP_{in}$ ($g/m^3$) | Flow Weighted Mean | 0.122 | 0.117 | 0.115 | 0.025 | 0.024 | 0.024 |
| | Arithmetic Mean | 0.118 | 0.118 | 0.118 | 0.023 | 0.023 | 0.023 |
| | Geometric Mean | 0.103 | 0.103 | 0.103 | 0.021 | 0.021 | 0.021 |
| | Max | 0.451 | 0.451 | 0.451 | 0.092 | 0.092 | 0.092 |
| | Min | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0 |
| $TP_{in}$ (kg) | Total | 266,935 | 230,122 | 201,194 | 47,169 | 41,005 | 35,894 |
| $Q_{out}$ ($m^3$/d) | Avg | 585,000 | 531,000 | 474,000 | 516,000 | 467,000 | 416,000 |
| | Max | 7,155,300 | 4,313,652 | 3,296,034 | 6,280,901 | 3,006,684 | 2,155,216 |
| | Min | 0 | 0 | 0 | 0 | 0 | 0 |
| $TP_{out}$ ($g/m^3$) | Avg | 0.016 | 0.018 | 0.019 | 0.010 | 0.011 | 0.011 |
| | Flow Weighted | 0.026 | 0.026 | 0.026 | 0.014 | 0.014 | 0.014 |
| | Max | 0.126 | 0.086 | 0.078 | 0.053 | 0.048 | 0.046 |
| | Min | 0.011 | 0.012 | 0.012 | 0.004 | 0.005 | 0.005 |
| $TP_{out}$ (kg) | Total | 54,900 | 49,056 | 43,913 | 26,544 | 24,014 | 21,309 |
| TP Eff. (%) | | 79.4 | 78.7 | 78.2 | 43.7 | 41.4 | 40.6 |
| Required Area (ac) | | 3,150 | 2,380 | 1,930 | 1,735 | 1,223 | 965 |
| Max Depth (ft) | | 3.90 | 3.30 | 3.10 | 3.90 | 3.30 | 3.10 |
| Avg Depth (ft) | | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 |
| Percent Dry Days | < 0.01 m | 0.87 | 0.73 | 0.56 | 2.4 | 2.4 | 2.4 |
| | < 0.15 m | 8.9 | 9.3 | 9.6 | 14.1 | 13.8 | 13.6 |
| Q bypass ($m^3$/d) | | 0 | 61,100 | 122,000 | 0 | 53,000 | 106,000 |
| TP bypass (kg) | | 0 | 36,800 | 65,740 | 0 | 6,160 | 11,300 |

*Hydraulic Enhancement Using Limerock Level Spreaders*

Our purpose in performing the TIS vs. footprint analyses is to suggest that an increase in the hydraulic efficiency of an SAV wetland (i.e, increasing the TIS parameter) can provide marked improvements in P removal performance. This is not a novel concept: it was proposed by us in our Phase II experimental design plan, and was discussed in detail in a recent memo by Dr. Bob Kadlec (2001).

What is novel about our approach is that rather than relying on the inherent hydraulic characteristics of the wetland plant community, or on conventional levees equipped with a small number of large culverts that can concentrate flows, we suggest that improved hydraulic performance can be achieved through the installation of a series of limerock berms perpendicular to flow. Such berms would serve as “level spreaders”, helping to distribute the flow evenly across the STA, thus reducing the short-circuiting effect observed in the STA cells. There may also be some secondary treatment benefits (i.e., particulate P removal, Ca and alkalinity addition) achieved as the flow travels through the berms, but we do not account for this in our analysis. It is important to note that such level spreaders will be entirely ineffective if farm or levee canals, which lie parallel to flow, are not filled or plugged prior to wetland hydration. In our cost estimate, we include a line item for excavating deep zones perpendicular to flow, and using this material to fill existing “parallel” farm canals.

It is imperative that hydraulic analyses be performed before final design and deployment of level spreaders in an STA cell. For our conceptual analysis, we suggest deploying berms that are 3.5’ high, therefore providing at least 6” of freeboard for peak flows (which would attain a 4’+ water depth). Lower flows would simply pass through the rock berm. As a rough calculation, each 1” of freeboard over a limerock level spreader provides the same cross-sectional area as ten 72” culverts situated in an STA-2 cross-levee.

Additionally, the level spreader design included in this analysis was based on the limerock berms deployed in the test cells, which were constructed with nominal 1” – 3” limerock (Figure 4-27). Hydraulic analyses may reveal that a larger rock size (e.g., 3 – 6”) may be more appropriate to pass flow, and reduce the possibility of plugging. An even more elaborate (and expensive) configuration would be one in which numerous small culverts are placed through each berm (Figure 4-28). For our analysis, the required number of culverts was determined by matching the flow conveyance of the existing inflow structures. A disadvantage of using the smaller culverts is that they will tend to re-concentrate flow as it passes through each limerock berm. While the re-concentration effect would be much less than what is currently occurring from the large cross-levee inflow culverts, it still could increase the likelihood of short-circuits. To help mitigate this concentrating effect, a deep trough could be installed just downstream of the limerock berms to provide a means of energy dissipation. While we expect that limerock level spreaders designed at the appropriate height and appropriate rock sizes won't require small culverts, we have included them in our level spreader cost analysis.

We suggest two possible methods for constructing the limerock level spreaders in the STAs. The first option involves working in the STA with the water drawn down. The general procedure will be to roll out a layer of the geotextile fabric and Tensar, followed by a layer of crusher run (end dumped). Another layer of Tensar would then be added (see Figure 4-27 for more construction details). The limerock would then be end dumped and distributed along the berm alignment. An alternative method of placing the limerock would be to fill barges with the necessary limerock before the STA is drained, then position them along the berm alignment. With the water level drawn down, a long-arm shovel can be used to offload the limerock to construct the berms.

*Excavation of Lateral Deep Zones*

Another aspect of the proposed design includes the excavation of lateral deep zones across the STA. These deep zones, 5 m wide by x 0.5 m deep, are designed to serve several purposes. First, they will provide a refuge for SAV vegetation during drought, which should facilitate re-inoculation of the wetland following rehydration. The second benefit is the use of the borrow material to fill the relic farm canals that run parallel to flow in the STA, thus eliminating their short-circuiting effects. A final potential benefit of these zones is to provide energy dissipation downstream of the limerock berms, should installation of the numerous small culverts be required.

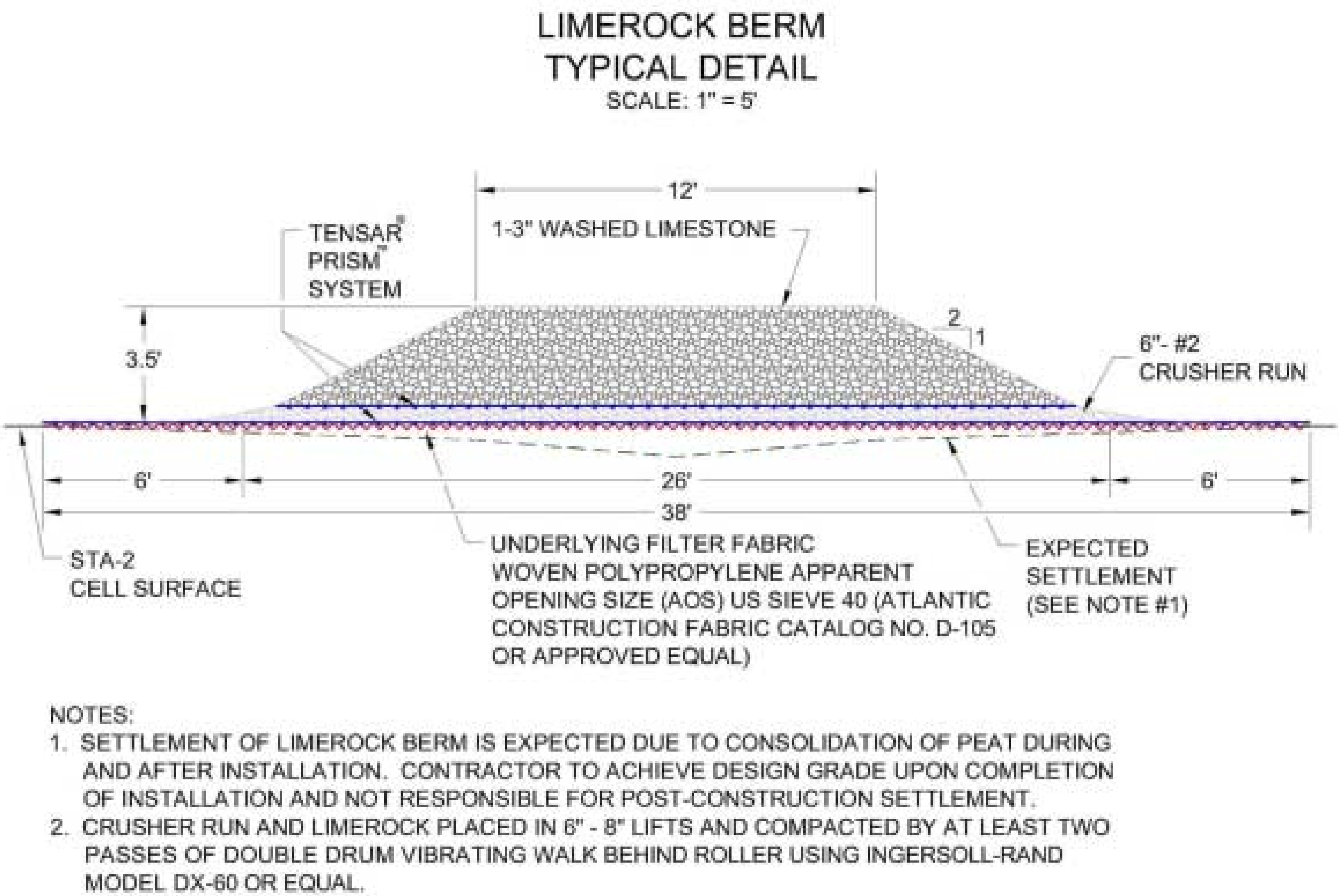



**Figure 4-27.** Schematic of limerock level spreader**.**

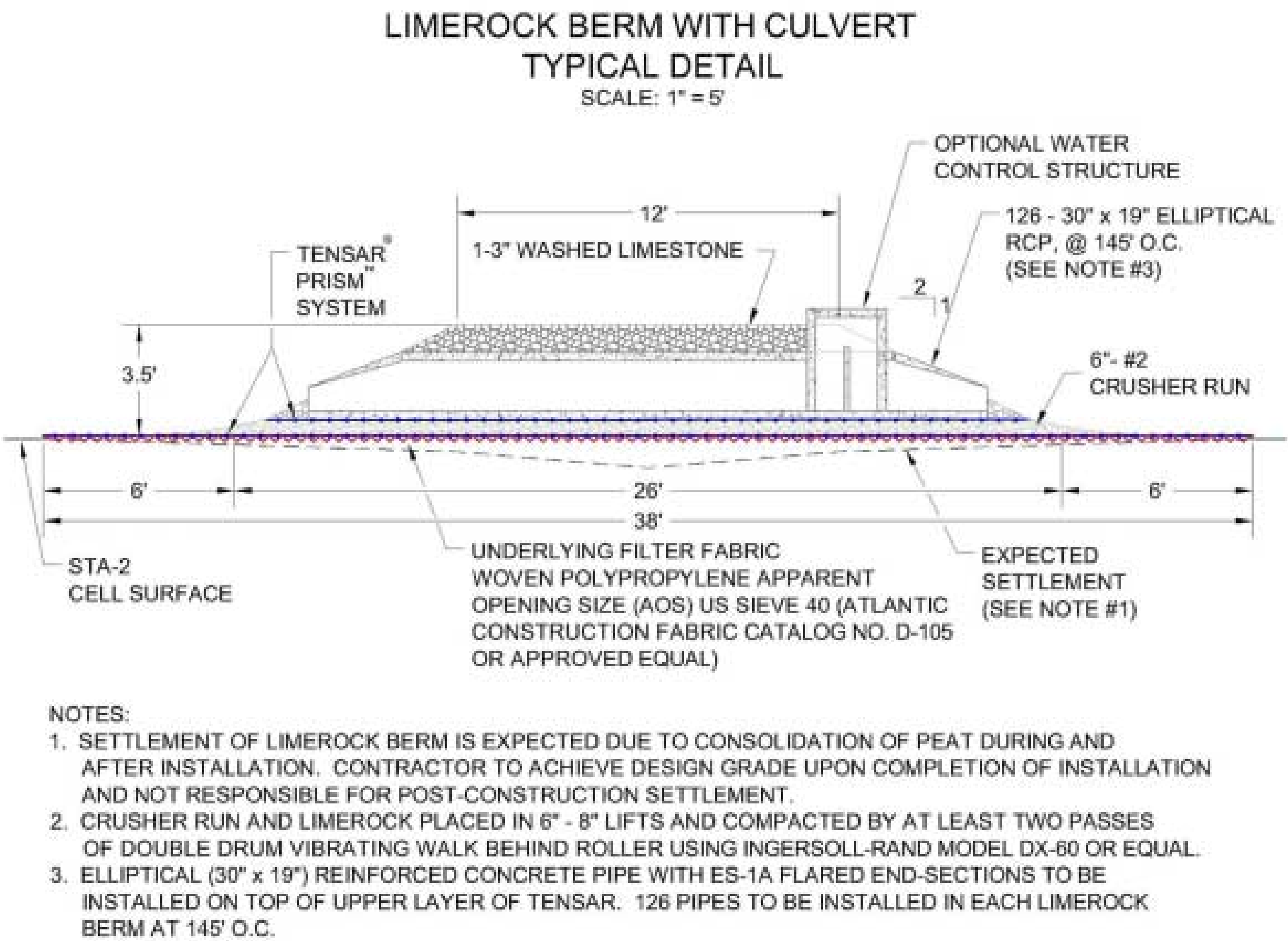



**Figure 4-28.** Schematic of level spreader equipped with culverts.

### 4.3.3 Credibility of Optimum Design with Respect to Hydraulics and Treatment Goals

Time series depictions of Post-BMP and Post-STA wetland hydraulic loading rates and depths for the optimum conceptual SAV wetland design under 0%, 10% and 20% bypass scenarios are provided in Figures 4-29 and 4-30. At first glance, it appears that the SAV wetlands will be challenged with variations in water depths and hydraulic loadings that will be so wide as to compromise performance. For example, HLR peaks of almost 60 cm / day are projected for the Post-BMP wetland, and periodic peaks ranging as high as 90 cm / day are predicted for the Post-STA wetland. In conjunction with these peaks, water depths in the wetland will fluctuate markedly, increasing from 0.2 m to 1.2 m in only a few days. It therefore is prudent to address whether or not there exist any data to substantiate P removal performance by an SAV wetland under these extreme inflow and depth variations. A second pertinent question relates to our projection that Cell 4 can achieve a long-term outflow target of 14 µg / L. For example, during the STSOC verification period, a time where optimum performance was targeted, Cell 4 achieved a mean outflow TP concentration of only 19 µg / L. For this assessment, we provide some observations on the performance of STA-1W Cell 4, the only full-scale, mature SAV system currently in operation.

*Perspective on the Characteristics and Performance of Cell 4*

Cell 4 is the final cell in series of a two-cell treatment train, which originally was termed the “western” flow path of the ENRP. The upstream cell is Cell 2, which initially was largely cattail, but is now a mixture of rooted cattail, floating emergent mats, SAV and open water devoid of vegetation. For purposes of this analysis, it is important to note that Cell 4 is atypical of most STA wetland cells, in that it is quite small (147 ha). The upstream wetland, Cell 2, is three times larger than Cell 4, at 440 ha.

Because of its small size, Cell 4 has been subject to unusually large hydraulic and P loadings, despite the fact that the ENRP historically was operated in a fairly low-flow, steady-state fashion. Part of our keen interest in Cell 4 is that it has performed quite well, particularly from an outflow concentration standpoint, despite these high hydraulic and P loadings. It also is important to note that the ability (or inability) of Cell 4 to achieve low outflow TP concentrations is highly dependent on the performance of the upstream Cell 2 community.

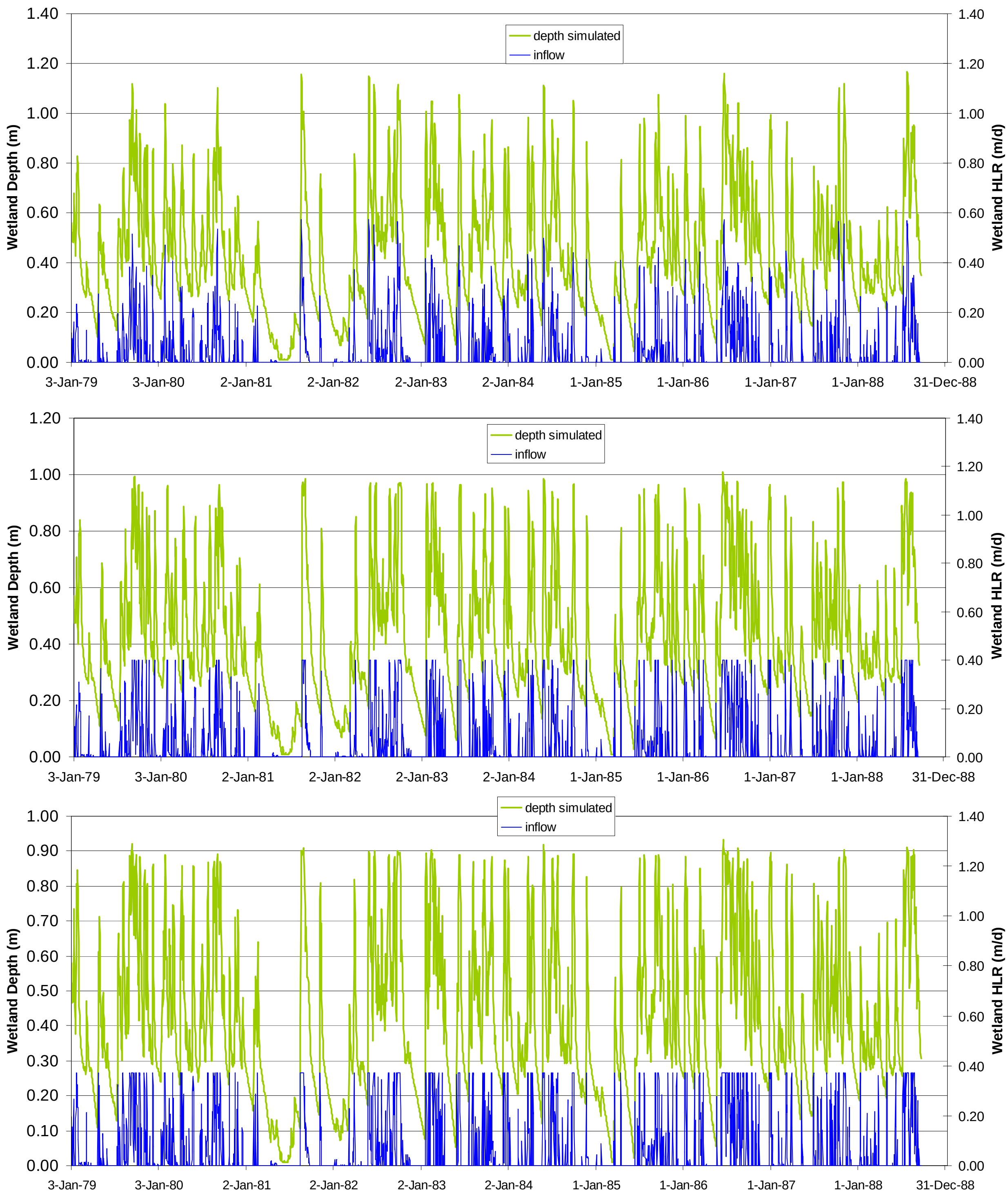



**Figure 4-29.** Time series depictions of Post-BMP wetland hydraulic loading rates and depths for the "optimum" design under 0% (top), 10% (middle) and 20% (bottom) bypass scenarios.

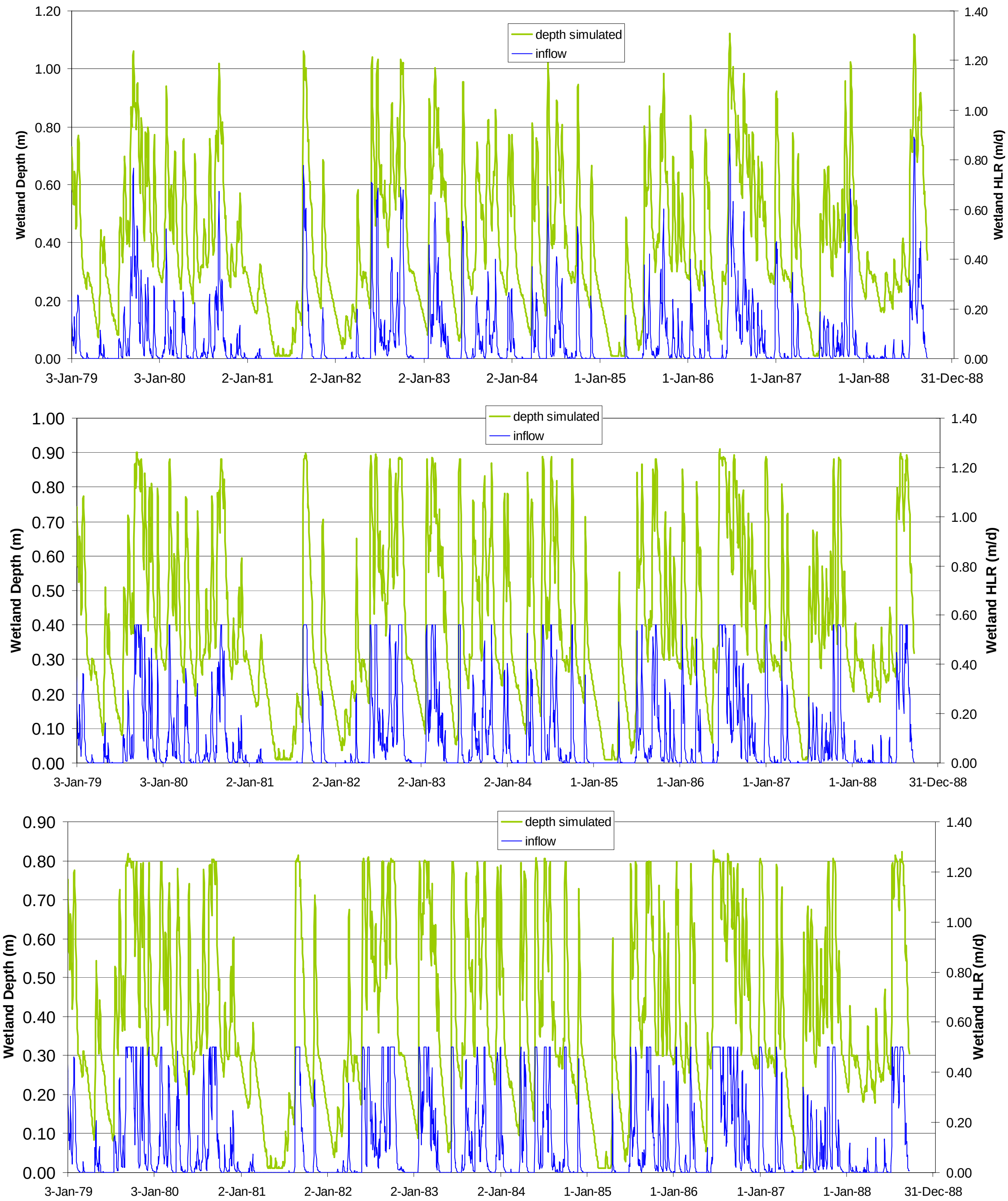



**Figure 4-30.** Time series depictions of Post-STA wetland hydraulic loading rates and depths for the "optimum" design under 0% (top), 10% (middle) and 20% (bottom) bypass scenarios.

*Cell 4 Performance in Response to Fluctuations in Flow, Depth and TP Loadings*

During the period that Cell 4 was operated as part of the ENRP, the wetland was subjected to relatively consistent hydraulic loadings. Since fall 2000, however, it has received highly variable loadings, with an extended period of stagnation, followed by dramatic flow peaks (Figure 4-31). To gain a better understanding of the P dynamics within Cell 4, we performed an extensive sampling of water column P in the wetland on several occasions during our Phase II effort. Results of two of these internal sampling efforts in fall 2001 are depicted in Figures 4-32 and 4-33. The 10/1/01 event is noteworthy because it represents a high flow event that also caused a rapid increase in wetland water depth (Figure 4-32). At the time of internal sampling, the top of the SAV beds throughout the wetland were covered by at least 15 cm of clear water. The reductions in P concentrations observed with distance from the inflow suggests that there is adequate mixing between this “overtopping” flow of water and the underlying vegetation. Figure 4-34 provides a perspective of flows, depths and Cell 4 inflow and outflow concentrations during both the 10/1 and 11/9 sampling events.

The 11/9/01 internal Cell 4 sampling event depicts the spatial profiles of TP and SRP within the wetland coincident with a rapid decline in flow (Figure 4-33). Inflow TP concentrations, and in particular, SRP concentrations, are extraordinarily high on this date, and on the preceding days during the high flow period. Despite these high inflow P concentrations, Cell 4 provided a reasonable level of treatment, reducing the four-day mean inflow TP levels of 123 µg/L to a mean outflow of 30 µg/L.

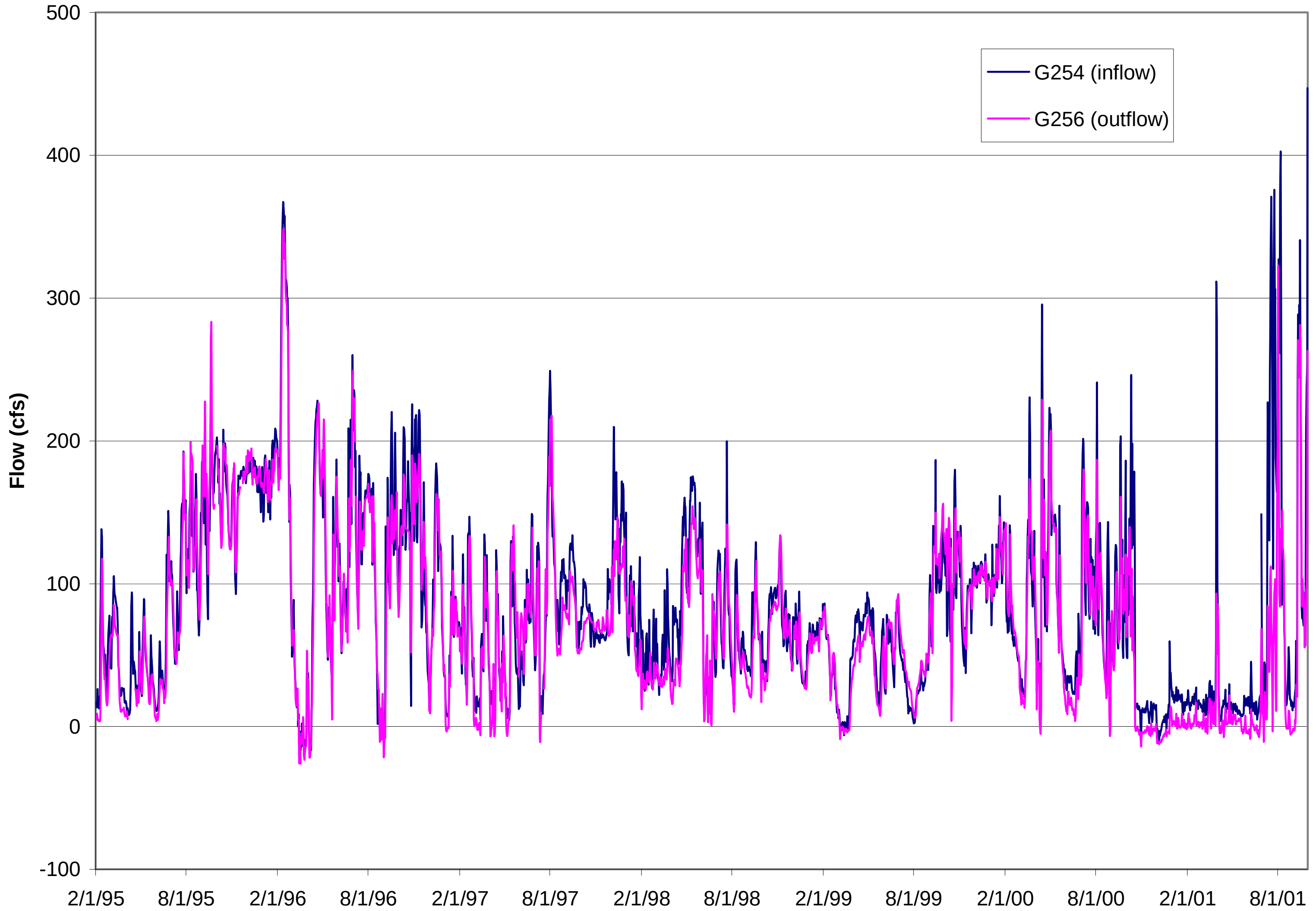
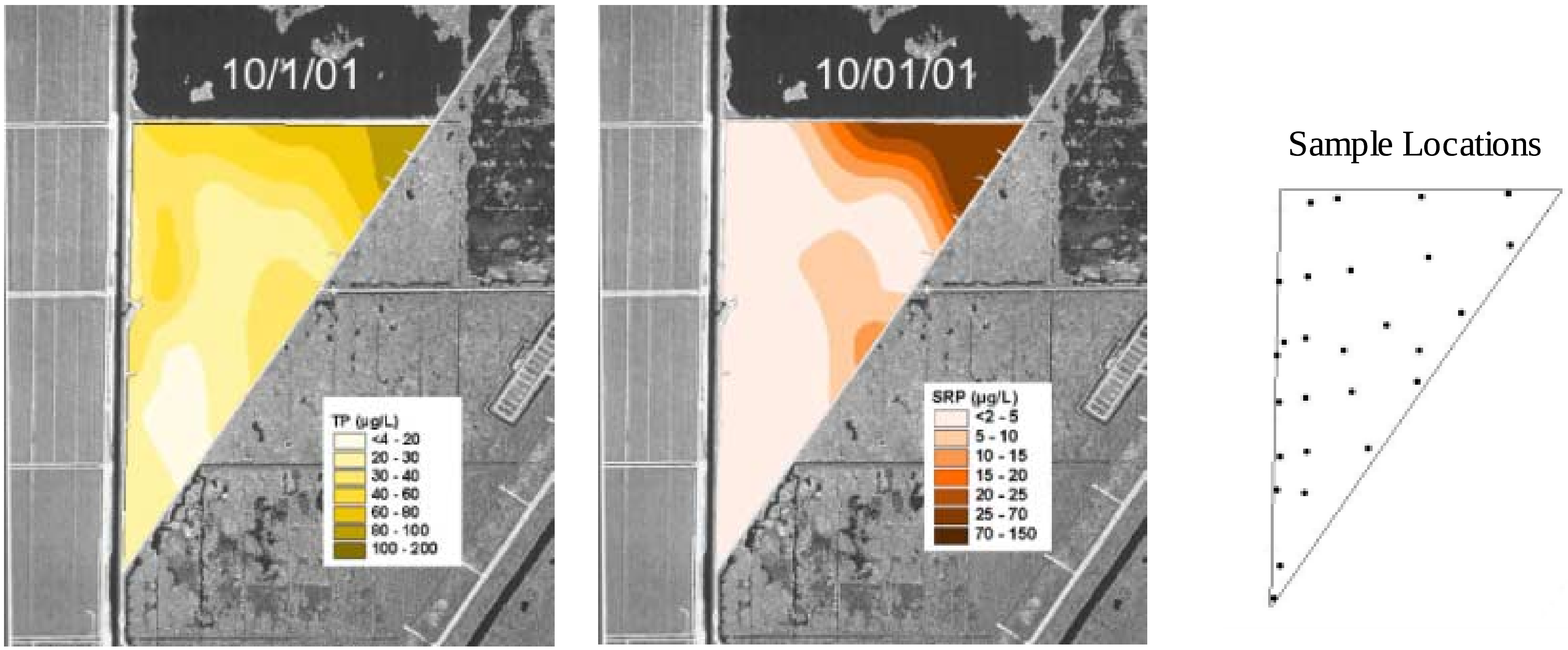
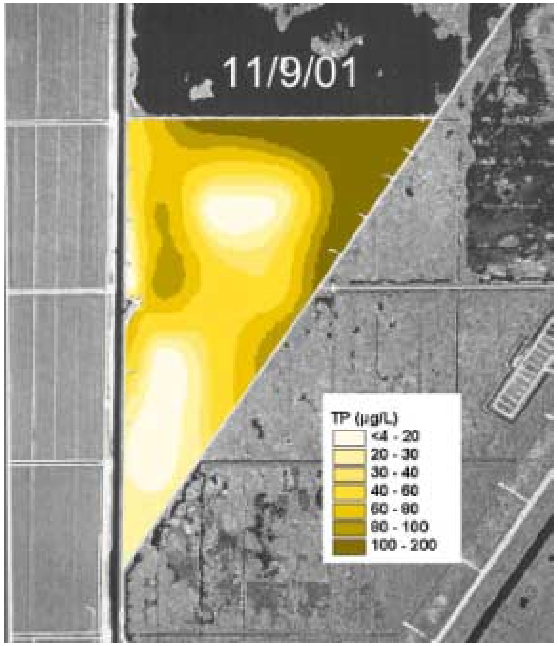


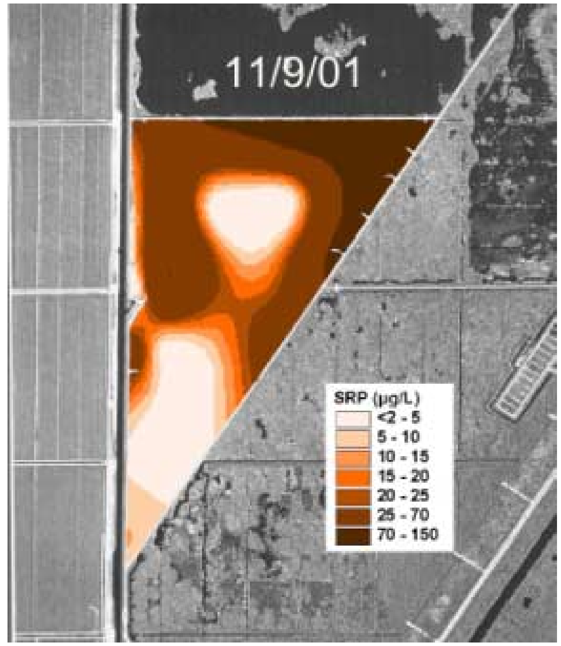

**Figure 4-31.** Historical flow record for the Cell 4 inflow levee culverts (G254) and the southernmost outflow culverts (G256).



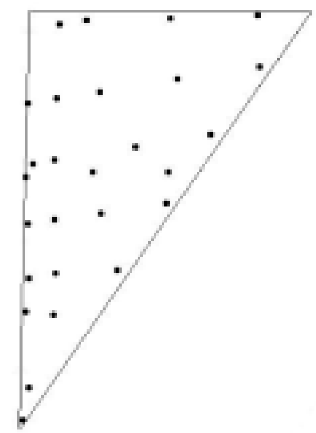

| **Internal Samping Date:** | **10/1/2001** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **9/25/2001** | **9/26/2001** | **9/27/2001** | **9/28/2001** | **9/29/2001** | **9/30/2001** | **10/1/2001** |
| Depth (ft) | 2.28 | 2.48 | 2.59 | 3.22 | 3.81 | 3.85 | 3.95 |
| G254 Flow (cfs) | 81.6 | 79.0 | 207.6 | 237.8 | 252.1 | 447.0 | 425.2 |
| G256 Flow (cfs) | 66.2 | 56.7 | 95.3 | 99.2 | 140.4 | 263.0 | 269.6 |
| | | | | | | | |
| | | | **9/27/2001** | **9/28/2001** | | | **10/1/2001** |
| TP in (µg/L) | | | 73 | 79 | | | 62 |
| TP out (µg/L) | | | | 20 | | | 22 |
| SRP in (µg/L) | | | 8 | 16 | | | |
| SRP out (µg/L) | | | | 1 | | | 3 |

**Figure 4-32.** Spatial characterization of Cell 4 water column TP and SRP concentrations on October 1, 2001. Beginning 9/27/01, the wetland was challenged with high inflows, which resulted in a rapid increase in water depth and G256 outflows**.**




Sample Locations



| **Internal Samping Date:** | **11/9/2001** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **11/3/2001** | **11/4/2001** | **11/5/2001** | **11/6/2001** | **11/7/2001** | **11/8/2001** | **11/9/2001** |
| Depth (ft) | 1.76 | 1.66 | 1.84 | 2.28 | 2.79 | 3.14 | 3.24 |
| G254 Flow (cfs) | 123.1 | 142.7 | 176.5 | 108.7 | 115.1 | 89.5 | 36.3 |
| G256 Flow (cfs) | 88.9 | 74.6 | 61.4 | 75.0 | 76.9 | 22.0 | 2.1 |
| | | | | | | | |
| | | | | **11/06/01** | **11/07/01** | **11/08/01** | **11/09/01** |
| TP in (µg/L) | | | | 110 | 115 | 131 | 134 |
| TP out (µg/L) | | | | 28 | 24 | 28 | 38 |
| SRP in (µg/L) | | | | 86 | 91 | 96 | 106 |
| SRP out (µg/L) | | | | 12 | 11 | 7 | 7 |

**Figure 4-33.** Spatial characterization of Cell 4 water column TP and SRP concentrations on November 9, 2001. The sampling was performed on the day of a dramatic decline in flow.

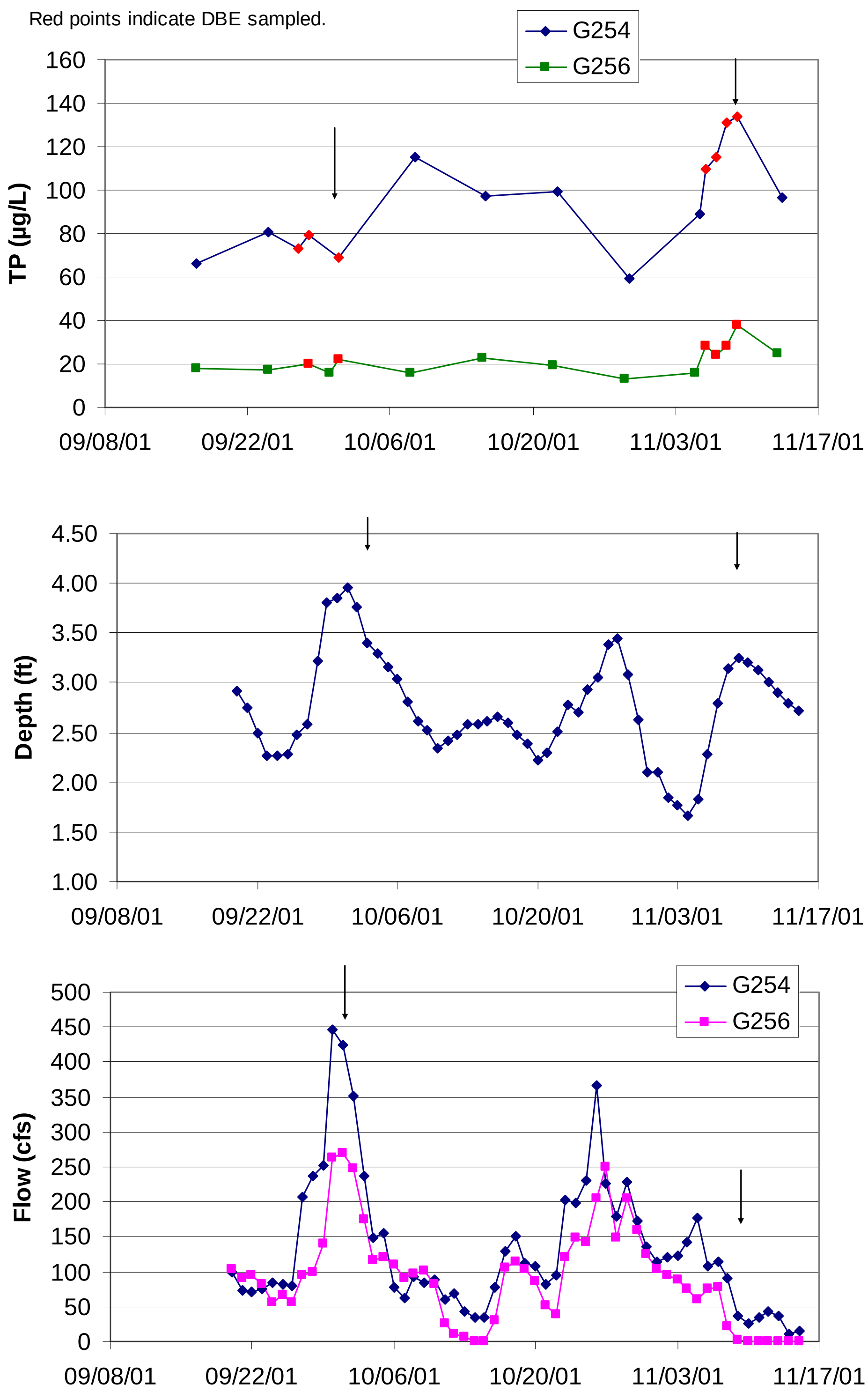



**Figure 4-34.** Cell 4 flow, water depths and inflow / outflow TP concentrations during fall 2001. On the TP graph, note that data points after 10 / 1 / 01 (with the exception of the data in red) did not pass QA / QC checks (sample holding times were exceeded).

*Constraints on Cell 4 Outflow Phosphorus Concentrations*

Our PMSAV simulation used for the optimum conceptual design of the Post-STA wetland predicts that a "back-end" SAV wetland can reduce TP levels from 25 µg/L to 14 µg/L, given an average hydraulic loading rate of 7.5 cm/day. This is equivalent to a mean inflow P loading of 0.7 gP/$m^2$-yr. A synopsis of annual Cell 4 operational conditions and performance is provided in Table 4-12. The performance data for 1998 and 1999 clearly show that Cell 4 is capable of providing outflow TP levels of 14 µg/L under HLRs and P loadings more challenging than that predicted in our PMSAV Post-STA projections. Additionally, the adverse impacts of excessive P loadings on outflow concentrations can be seen in the 2000 performance data (Table 4-12).

**Table 4-12.** A synopsis of annual Cell 4 operational conditions and performance from 2/1/1995 – 12/31/2000.

| | TP Inflow† (µg/L) | TP Outflow† (µg/L) | TP Load (g/$m^2$/yr) | Mass Removal (g/$m^2$/yr) | HLR (cm/day) |
|---|---|---|---|---|---|
| 1995 | 30 | 21 | 1.72 | 0.72 | 16.5 |
| 1996 | 57 | 26 | 3.69 | 1.63 | 21.3 |
| 1997 | 31 | 21 | 1.48 | 0.58 | 13.0 |
| 1998 | 39 | 14 | 1.79 | 1.16 | 12.0 |
| 1999 | 52 | 14 | 2.45 | 1.91 | 10.8 |
| 2000 | 80 | 28 | 3.48 | 2.06 | 12.3 |

†Arithmetic mean

We were tasked during the Cell 4 STSOC "verification" period to operate Cell 4 in such a fashion so as to achieve "optimum" performance, which included an attempt to attain the lowest possible outflow concentrations. We therefore requested that Cell 4 be operated at a moderate, steady hydraulic loading of about 100 cfs (ca. 17 cm/day HLR) during the verification period, and District operational personnel were able to effectively provide this consistent flow rate. Inflow TP concentrations to Cell 4 during this period, however, were high, averaging 52 µg/L. As noted in Section 3, outflow TP concentrations from Cell 4 during the STSOC verification period averaged 19 µg/L. As Cell 4 inflow concentrations declined during the sampling period, the Cell 4 outflow achieved a minimum TP concentration during the period of 13 µg/L (Figure 3-6). This performance suggests that if the inflow TP concentration to Cell 4 was lower, then a lower average outflow TP concentration could have been attained.

Phosphorus removal performance by the upstream wetland, Cell 2, is an important determinant of the P loadings to Cell 4. Unfortunately, during the verification period, Cell 2 was exporting, rather than removing P (Figure 4-35). Average TP concentrations increased during passage through Cell 2 from 40 to 52 µg/L, but were then reduced by Cell 4 to 19 µg/L. We observed a similar trend during October and November 2001: the large upstream Cell 2 wetland was consistently exporting P during the period that Cell 4 was challenged with extreme flow pulses and high inflow P concentrations.

These data reinforce the concept that successful "back-end" performance of SAV systems, such as Cell 4, can be achieved only if the upstream wetlands provide at least a moderate level of treatment. Cell 4 appears to be resilient to short-term increases in P loading, but prolonged periods of high TP loading, such as occurred during late 1999, can cause marked increases in outflow TP concentrations.

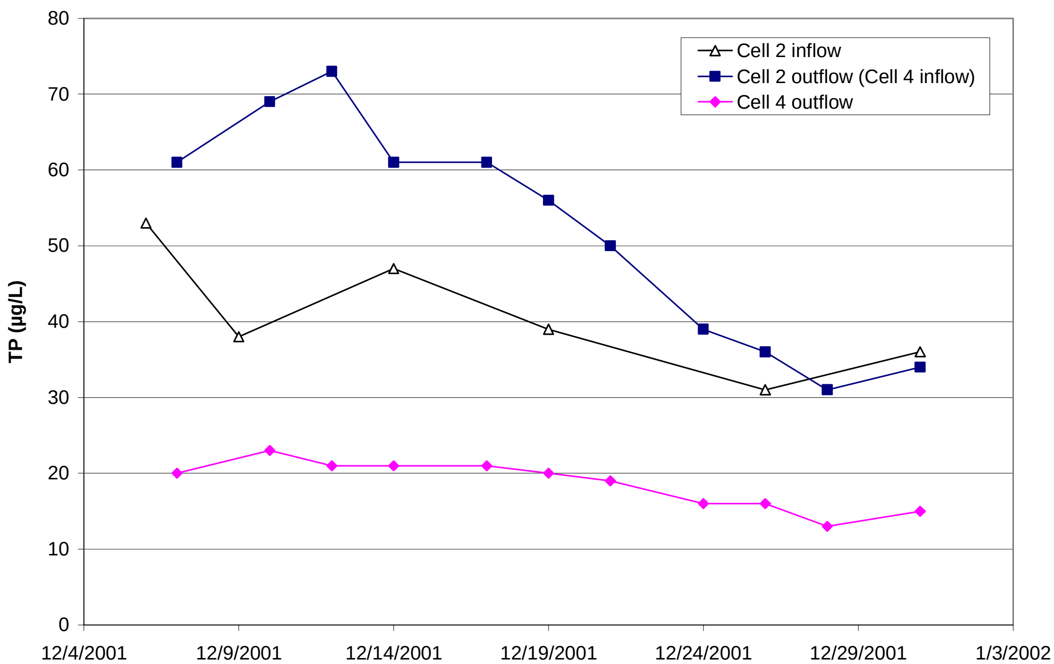



**Figure 4-35.** Inflow and outflow TP concentrations for Cells 2 and 4 during the Cell 4 STSOC 'verification' period.

## 4.4 Cost Estimates

### 4.4.1 STSOC Conceptual Designs

Costing and design summaries for the STSOC Post-BMP and Post-STA analyses are provided in Tables 4-13 – 4-21. For the STSOC Post-BMP analysis, we assumed an SAV wetland scaled-up directly from NTC-15 findings. For this costing scenario, we assume that the wetland achieves an outflow TP concentration of 26 μg/L and a hydraulic efficiency (TIS) of 2. No internal features are incorporated to improve system hydraulics. The area requirement for this system is 4,375 acres, or 68% of the STA-2 footprint. Because vegetation management is the only cost associated with this scenario, the 50 year present worth costs are quite low ($ 4,167,704 without STA-2 costs for 0% bypass scenario).

For the STSOC Post-STA analysis, we assumed an SAV wetland scaled-up from the Cell 4 STSOC verification period. For this costing scenario, we assume that the wetland receives a TP inflow concentration of 50 μg/L and achieves an outflow TP concentration of 20 μg/L. The hydraulic efficiency is established to be poor (TIS of 1). No internal features are incorporated to improve system hydraulics. The wetland is constructed outside of the STA-2 footprint, and the area requirement is 3,150 acres. In part because of the poor hydraulic efficiency, and also because of the need to purchase land and to construct additional levees, the 50 year present worth costs are quite high ($ 72,933,064 without STA-2 costs for 0% bypass scenario).

**Table 4-13.** SAV wetland design criteria summary (STSOC Post-BMP).

| Design Criteria | STSOC Post-BMP Bypass % 0 | 10 | 20 |
|---|---|---|---|
| Total Treatment Area (acres) | 4,375 | 3,225 | 2,625 |
| No. of Treatment Cells | | Fits within STA-2 Footprint | |
| Treatment Cell Area, (acres) | | Fits within STA-2 Footprint | |
| Average Water Depth (ft) | 1.4 | 1.4 | 1.4 |
| Maximum Water Depth (ft) | 3.9 | 3.3 | 3.1 |
| Total Land Required (ac) | | Fits within STA-2 Footprint | |
| Inflow Canal Length (miles) | | " " | |
| No. of Inflow Control Structures per Cell | | " " | |
| Inflow Levee Length (miles) | | " " | |
| Inflow Levee Side Slope (H:V) | | " " | |
| Inflow Levee Height (ft) | | " " | |
| Outflow Canal Length (miles) | | " " | |
| No. of Outflow Control Structures per Cell | | " " | |
| Type of Outflow Control Structures | | " " | |
| Outflow Levee Length (miles) | | " " | |
| Outflow Levee Height (ft) | | " " | |
| Interior Levee Length (miles) | | " " | |
| Interior Levee Height (ft) | | " " | |
| Side Levee Length (miles) | | " " | |
| Side Levee Height (ft) | | " " | |
| By-pass Canal Length (miles) | | " " | |
| No. of Bypass Control Structures | | " " | |
| Bypass Levee Length (miles) | | " " | |
| Seepage Canal Length (miles) | | " " | |
| Seepage Levee Length (miles) | | " " | |
| Side Seepage Canal Length (miles) | | " " | |
| Side Seepage Levee Length (miles) | | " " | |

**Table 4-14.** Summary of model results for design STSOC Post-BMP.

**STSOC Post-BMP**
**Post BMP, $P_{out}$ = 26 ppb**
**TIS = 2**

**Model Results Summary**

| Bypass (%) | Required Area (ac) | Required Length (m) | $P_{removed}$ (kg/yr) |
|---|---|---|---|
| 0 | 4,375 | 3,128 | 20,587 |
| 10 | 3,225 | 2,300 | 17,449 |
| 20 | 2,625 | 1,886 | 15,159 |

**Table 4-15.** SAV wetland conceptual design cost summary (STSOC Post-BMP and STSOC Post-STA).

| Item/Task | Unit | Unit cost | Source/Assumptions |
|---|---|---|---|
| Eradication of Existing Vegeatation | $/acre | $ 200 | Cost to spray existing vegetation prior to SAV innoculation. |
| Maintenance - Vegetation Control | $/acre | $ 25 | Annual cost to spray for invasive species. |
| Maintenance - Post drought eradication | $/acre | $ 10 | Assumes post drought eradication spraying for a period of 5 years during 50-year project life @ $100/ac. Cost reduced to annual rate of $10/acre. |
| 50' inflow weir with gate | per structure | $ 110,000 | SFWMD Unit Costs |
| 5' X 35' outflow box culvert with gate | per structure | $ 207,000 | SFWMD Unit Costs |
| By-pass structure | per structure | $ 5,270 | SFWMD Unit Costs |
| Internal- 8' (4.5' SWD)-6' top width | $/mile | $ 281,000 | SFWMD Unit Costs |
| External- 8' (4.5' SWD) | $/mile | $ 485,000 | SFWMD Unit Costs |
| Demolition Costs | Lump sum | | Assumes 20% of capital costs per SFWMD |
| Replacement Items | Lump sum | | Assumes 50% of costs replaced once at 25 years, per SFWMD |
| Salvage of Land | Lump sum | | SFWMD Unit Costs |
| Sampling and monitoring | Lump sum | $ 3,120 | SFWMD Unit Costs |

**Table 4-16.** Summary of costs for full scale SAV wetland implementation (STSOC Post-BMP) (no STA-2 costs).

| Cost Component | STSOC Post-BMP<br>Post BMP, $P_{out}$ = 26 ppb, 2 TIS | | |
|---|---|---|---|
| | % Bypass | | |
| | 0% | 10% | 20% |
| Capital | $875,000 | $659,173 | $539,173 |
| Operating | $3,289,584 | $2,424,894 | $1,973,751 |
| Demolition/Replacement | $0 | $0 | $0 |
| Salvage | $0 | $0 | $0 |
| Lump Sum/Contingency | $3,120 | $3,120 | $3,120 |

**Table 4-17.** Summary of present worth costs for the SAV wetland conceptual design (STSOC Post-BMP).

| Target | Bypass | 50-Year Present Worth | | $/Pound TP Removed | | $/1000 gal. Treated | |
|---|---|---|---|---|---|---|---|
| | | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 |
| 26 ppb | 0% | $4,167,704 | $166,970,045 | $1.8 | $74 | $0.00 | $0.06 |
| | 10% | $3,087,186 | $165,889,527 | $1.6 | $86 | $0.00 | $0.07 |
| | 20% | $2,516,043 | $165,318,384 | $1.5 | $99 | $0.00 | $0.07 |

**Table 4-18.** SAV wetland design criteria summary (STSOC Post-STA).

| Design Criteria | STSOC Post-STA | | |
|---|---|---|---|
| | Bypass % | | |
| | 0 | 10 | 20 |
| Total Treatment Area (acres) | 3,150 | 2,250 | 1,735 |
| No. of Treatment Cells | 1 | 1 | 1 |
| Treatment Cell Area, (acres) | 3,150 | 2,250 | 1,735 |
| Average Water Depth (ft) | 1.4 | 1.4 | 1.4 |
| Maximum Water Depth (ft) | 3.9 | 3.3 | 3.1 |
| Total Land Required (ac) | 3,308 | 2,363 | 1,822 |
| Inflow Canal Length (miles) | 1.8 | 1.5 | 1.3 |
| No. of Inflow Control Structures per Cell | 9 | 9 | 9 |
| Inflow Levee Length (miles) | 1.8 | 1.5 | 1.3 |
| Inflow Levee Side Slope (H:V) | 3.0 | 3.0 | 3.0 |
| Inflow Levee Height (ft) | 8.0 | 8.0 | 8.0 |
| Outflow Canal Length (miles) | 1.8 | 1.5 | 1.3 |
| No. of Outflow Control Structures per Cell | 3 | 3 | 3 |
| Type of Outflow Control Structures | Gated Culvert | Gated Culvert | Gated Culvert |
| Outflow Levee Length (miles) | 1.8 | 1.5 | 1.3 |
| Outflow Levee Height (ft) | 8.0 | 8.0 | 8.0 |
| Interior Levee Length (miles) | 0.0 | 0.0 | 0.0 |
| Interior Levee Height (ft) | 0.0 | 0.0 | 0.0 |
| Side Levee Length (miles) | 2.7 | 2.3 | 2.0 |
| Side Levee Height (ft) | 8.0 | 8.0 | 8.0 |
| By-pass Canal Length (miles) | 2.7 | 2.3 | 2.0 |
| No. of Bypass Control Structures | 1 | 1 | 1 |
| Bypass Levee Length (miles) | 2.7 | 2.3 | 2.0 |
| Seepage Canal Length (miles) | 1.8 | 1.5 | 1.3 |
| Seepage Levee Length (miles) | 1.8 | 1.5 | 1.3 |
| Side Seepage Canal Length (miles) | 2.7 | 2.3 | 2.0 |
| Side Seepage Levee Length (miles) | 2.7 | 2.3 | 2.0 |

**Table 4-19.** Summary of model results and technology specific structures for STSOC Post-STA.

## STSOC Post-STA

**Post STA, $P_{in}$ = 50, $P_{out}$ = 20 ppb**

**TIS = 1**

### Model Results Summary

| Bypass (%) | Required Area (ac) | Required Length (m) | $P_{removed}$ (kg/yr) |
|---|---|---|---|
| 0 | 3,150 | 2,254 | 5,813 |
| 10 | 2,250 | 1,610 | 4,917 |
| 20 | 1,735 | 1,242 | 4,224 |

### Technology Specific Structures

| | Canals | | | | | | Levees | | |
|---|---|---|---|---|---|---|---|---|---|
| | Seepage | | Inflow | | Outflow | | Perimeter | Inflow | Outflow |
| Bypass (%) | Length (mi) | Volume ($yd^3$) | Length (mi) | Volume ($yd^3$) | Length (mi) | Volume ($yd^3$) | Length (mi) | Length (mi) | Length (mi) |
| 0 | 6.3 | 714,135 | 1.8 | 307,475 | 1.8 | 566,774 | 6.3 | 1.8 | 1.8 |
| 10 | 5.4 | 603,554 | 1.5 | 259,864 | 1.5 | 479,011 | 5.4 | 1.5 | 1.5 |
| 20 | 4.7 | 529,999 | 1.3 | 228,194 | 1.3 | 420,634 | 4.7 | 1.3 | 1.3 |

**Table 4-20.** Summary of costs for full scale SAV wetland implementation (STSOC Post-STA) (no STA-2 costs).

| Cost Component | STSOC Post-STA<br>Post STA, $P_{in}$ = 50 ppb, $P_{out}$ = 20 ppb, 1 TIS | | |
|---|---|---|---|
| | % Bypass | | |
| | 0% | 10% | 20% |
| Capital | $58,414,540 | $50,182,723 | $30,489,185 |
| Operating | $2,695,969 | $1,968,547 | $1,547,587 |
| Demolition/Replacement | $13,481,089 | $12,675,958 | $11,305,540 |
| Salvage | ($2,061,653) | ($1,472,609) | ($1,135,545) |
| Lump Sum/Contingency | $403,120 | $403,120 | $403,120 |

**Table 4-21.** Summary of present worth costs for the SAV wetland conceptual design (STSOC Post-STA).

| Target | Bypass | 50-Year Present Worth | | $/Pound TP Removed | | $/1000 gal. Treated | |
|---|---|---|---|---|---|---|---|
| | | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 |
| 20 ppb | 0% | $72,933,064 | $235,735,405 | $114 | $368 | $0.03 | $0.10 |
| | 10% | $63,757,739 | $226,560,080 | $118 | $418 | $0.03 | $0.10 |
| | 20% | $42,609,886 | $205,412,227 | $91 | $441 | $0.02 | $0.10 |

### 4.4.2 Optimum Conceptual Design

We also performed cost analyses for the SAV/LR wetland with optimized hydraulic performance. For this analysis, the Post-BMP wetland reduces TP levels from 122 to 26 µg/L, and the subsequent Post STA wetland reduces TP concentrations further, from 26 to 14 µg/L. From the plots of the TIS simulations, an optimum TIS number of 5 was selected from the Post-BMP model runs, and a TIS number of 2 was selected for the Post-STA model runs. As can be seen from the area requirements, this scenario can fit within the current footprint of STA-2 for all three bypass (10%, 20% and 30%) scenarios. Because no new "conventional" STA infrastructure is required (pumps, land, levees, canals, etc.), additional costs required for this scenario were primarily limited to the limerock berms, the lateral deep zones, smaller culverts for the limerock berms (included in the cost, even though their use is not anticipated), and herbicides for initial eradication of existing vegetation as well as for annual maintenance. A summary of design criteria and project specific structures and costs are shown in Tables 4-22 – 4-24. The 50 year present worth cost of this system, treating to an outflow TP level of 14 µg/L with 0% bypass, is $23,537,214 without STA-2 costs, and $186,339,555 including STA-2 costs. The low cost (expressed in $/lb) of P removed highlights the benefit of being able to fit the SAV/LR system within the existing STA-2 footprint (Tables 4-25 and 4-26).

For comparison purposes, we also developed cost estimates for two additional scenarios that relate or provide context to this optimum design. A synopsis of each is provided herein, and specific details are provided in the appendix.

Scenario 1A. We developed costs for a system similar to Scenario 1 (SAV wetland equipped with level spreaders), but which also includes two "conventional" internal earthen levees equipped with large culverts. The first levee separates the "front-end" mixed vegetation community from the Post-BMP SAV wetland, and the second levee separates the Post-BMP and Post-STA SAV wetlands. Costs for this design that incorporates "traditional" levees are not substantially higher than those for of our principal conceptual design. The addition of the two earthen levees increases the 50 year present worth costs (without STA-2 costs) from $23,537,214 to $27,775,314.

Scenario 2. To demonstrate the potential cost savings attainable from hydraulic optimization, we calculated system costs for a Post-BMP and Post-STA SAV wetland configuration with extremely poor hydraulic efficiency. For this scenario, we left intact the some of the internal modifications (two limerock level spreaders), but assumed that they provided no benefits. Indeed, to present the worst possible case, we assume that each SAV system (Post-STA and Post-BMP) behaves hydraulically like a wetland with TIS = 1. The land area required for this hydraulically-compromised system exceeds the STA-2 footprint, and the resulting present worth costs are high ($104,018,965, without STA-2 costs).

**Table 4-22.** SAV wetland design criteria summary (optimum design).

| Design Criteria | Bypass % | | |
|---|---|---|---|
| | 0 | 10 | 20 |
| Total Treatment Area (acres) | 4,885 | 3,603 | 2,895 |
| No. of Treatment Cells | | Fits within STA-2 Footprint | |
| Treatment Cell Area, (acres) | | Fits within STA-2 Footprint | |
| Average Water Depth (ft) | 1.4 | 1.4 | 1.4 |
| Maximum Water Depth (ft) | 3.9 | 3.3 | 3.1 |
| Total Land Required (ac) | | Fits within STA-2 Footprint | |
| Inflow Canal Length (miles) | | " " | |
| No. of Inflow Control Structures per Cell | | " " | |
| Inflow Levee Length (miles) | | " " | |
| Inflow Levee Side Slope (H:V) | | " " | |
| Inflow Levee Height (ft) | | " " | |
| Outflow Canal Length (miles) | | " " | |
| No. of Outflow Control Structures per Cell | | " " | |
| Type of Outflow Control Structures | | " " | |
| Outflow Levee Length (miles) | | " " | |
| Outflow Levee Height (ft) | | " " | |
| Interior Levee Length (miles) | | " " | |
| Interior Levee Height (ft) | | " " | |
| Side Levee Length (miles) | | " " | |
| Side Levee Height (ft) | | " " | |
| By-pass Canal Length (miles) | | " " | |
| No. of Bypass Control Structures | | " " | |
| Bypass Levee Length (miles) | | " " | |
| Seepage Canal Length (miles) | | " " | |
| Seepage Levee Length (miles) | | " " | |
| Side Seepage Canal Length (miles) | | " " | |
| Side Seepage Levee Length (miles) | | " " | |

**Table 4-23.** Summary of model results and technology specific structures for optimum design.

## Optimum Design

**Post BMP $P_{out}$ = 26 ppb**

**Post STA $P_{in}$ = 25 ppb, $P_{out}$ = 14 ppb**

**TIS = 7**

### Model Results Summary

| Bypass (%) | Treatment Type | Required Area (ac) | Required Length (m) | $P_{removed}$ (kg/yr) |
|---|---|---|---|---|
| 0 | Post BMP | 3,150 | 2,254 | 20,513 |
| | Post STA | 1,735 | 1,242 | 2,133 |
| | Total | 4,885 | 3,496 | 22,646 |
| 10 | Post BMP | 2,380 | 1,702 | 17,511 |
| | Post STA | 1,223 | 874 | 1,747 |
| | Total | 3,603 | 2,576 | 19,258 |
| 20 | Post BMP | 1,930 | 1,380 | 15,185 |
| | Post STA | 965 | 690 | 1,496 |
| | Total | 2,895 | 2,070 | 16,681 |

### Technology Specific Structures

| | Lateral Deep Zones | | Limerock Berm | | Farm Canal Replacement | |
|---|---|---|---|---|---|---|
| Bypass (%) | Required No. | Volume ($yd^3$) | Length (mi.) | Area ($yd^2$) | Required No. | Volume ($yd^3$) |
| 0 | 16 | 195,670 | 24 | 428,028 | 24 | 428,227 |
| 10 | 14 | 171,211 | 24 | 428,028 | 24 | 315,536 |
| 20 | 10 | 122,294 | 24 | 428,028 | 24 | 253,556 |

**Table 4-24.** SAV wetland optimum conceptual design cost summary.

| Item/Task | Unit | Unit cost | Source/Assumptions |
|---|---|---|---|
| Lateral Deep Zones | $/yd$^3$ | $ 5.00 | Shallow canal excavation cost from SFWMD plus additional $1.50 to place material in exisiting farm canals to plug short circuits. Assumed 1.5' deep, 3:1 side slopes, 7.5' base. |
| Farm Canals | $/yd$^3$ | $ 2.50 | Cost to replace farm canals at end of project. Assumes 3' deep, 2:1 side slope, 8' base, app. 700' o.c. |
| Limerock Berms | $/mile | $ 130,044 | Assumes 3.5' high, 26' base, DOT Base Aggregate @ $10/yd$^3$ installed. |
| Tensar and Filter Fabric | $/yd$^2$ | $ 9.00 | Assumes 2 layers of Tensar and one layer of filter fabric under limerock berms. |
| Internal Culverts | ea | $ 2,640 | If head loss through limerock berms proves to be problematic, install 19" x 30" elliptical RCP's at approximately 45m o.c. Includes material and installation costs. |
| Eradication of Existing Vegeatation | $/acre | $ 200 | Cost to spray existing vegetation prior to SAV innoculation. |
| Maintenance - Vegetation Control | $/acre | $ 25 | Annual cost to spray for invasive species. |
| Maintenance - Post drought eradication | $/acre | $ 10 | Assumes post drought eradication spraying for a period of 5 years during 50-year project life @ $100/ac. Cost reduced to annual rate of $10/acre. |
| 50' inflow weir with gate | per structure | $ 110,000 | SFWMD Unit Costs |
| 5' X 35' outflow box culvert with gate | per structure | $ 207,000 | SFWMD Unit Costs |
| By-pass structure | per structure | $ 5,270 | SFWMD Unit Costs |
| Internal- 8' (4.5' SWD)-6' top width | $/mile | $ 281,000 | SFWMD Unit Costs |
| External- 8' (4.5' SWD) | $/mile | $ 485,000 | SFWMD Unit Costs |
| Demolition Costs | Lump sum | | Assumes 20% of capital costs per SFWMD |
| Replacement Items | Lump sum | | Assumes 50% of costs replaced once at 25 years, per SFWMD |
| Salvage of Land | Lump sum | | SFWMD Unit Costs |
| Sampling and monitoring | Lump sum | $ 3,120 | SFWMD Unit Costs |

**Table 4-25.** Summary of costs for full scale SAV wetland implementation (optimum design) (no STA-2 costs).

| Cost Component | % Bypass 0% | 10% | 20% |
|---|---|---|---|
| Capital | $16,698,384 | $15,898,606 | $15,205,643 |
| Operating | $3,673,056 | $2,709,114 | $2,176,765 |
| Demolition/Replacement | $3,162,654 | $3,162,654 | $3,162,654 |
| Salvage | $0 | $0 | $0 |
| Lump Sum/Contingency | $3,120 | $3,120 | $3,120 |

**Table 4-26.** Summary of present worth costs for the SAV wetland conceptual design (optimum design).

| | | 50-Year Present Worth | | $/Pound TP Removed | | $/1000 gal. Treated | |
|---|---|---|---|---|---|---|---|
| Target | Bypass | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 | Without STA-2 | With STA-2 |
| 14 ppb | 0% | $23,537,214 | $186,339,555 | $9 | $75 | $0.01 | $0.08 |
| | 10% | $21,773,494 | $184,575,835 | $10 | $87 | $0.01 | $0.08 |
| | 20% | $20,548,182 | $183,350,523 | $11 | $100 | $0.01 | $0.09 |

# Section 5: STSOC Analysis

In this section, we address the individual components of the STSOC analysis, dividing these, where appropriate, into Post-BMP and Post-STA categories.

## 5.1 Level of Phosphorus Concentration Reduction

### 5.1.1 Post-BMP

Outflow concentrations from SAV/LR systems that receive Post-BMP waters are controlled largely by P loading rate, which in turn is a function of HLR and inflow P concentration. At a moderate HLR (e.g., 11 cm/day), SAV wetlands can provide outflow TP concentrations of 25 µg/L. Test cells NTC-1 and NTC-15 achieved this level of P removal, as did the "low" HLR mesocosm at the north supplemental technology site (Table 1.1). During the Post-BMP STSOC calibration and verification periods, NTC-15 provided outflow concentrations of 23 and 34 µg/L, respectively. The higher outflow TP concentration observed during the verification period was due both to the higher HLR (approx. 11 vs 22 cm/day) and influent P concentrations (72 vs. 112 µg/L TP) that occurred at this time.

Unless the initial soils are highly enriched with fertilizer P, the Post-BMP SAV wetlands appear to quickly achieve the outflow concentrations noted above (approx. 25 µg/L), since the rapid removal of water column SRP essentially masks the small-to-moderate soil P fluxes. However, under relatively high loadings of Post-BMP waters, the sediments that form do not appear to be as stable as those that accrue in SAV wetlands treating Post-STA waters.

### 5.1.2 Post-STA

Based on a review of performance data from numerous platforms, we believe that 14 µg/L is a reasonable long-term minimum outflow concentration for SAV/LR systems used for Post-STA treatment (Table 1.1). On an intermittent, short-term basis, all SAV platforms (mesocosms, test cells, full-scale) have achieved outflow TP concentrations of 10 µg/L and even lower, but they do not appear to provide this level of treatment on a sustainable basis (see Figure 1.4). All SAV systems that achieved the long-term 14 µg/L outflow TP levels were established on muck soils. Cultivation of SAV on a limerock substrate does not improve P removal performance.

## 5.2 Total Phosphorus Load Reduction

### 5.2.1 Post-BMP

During the calibration period, NTC-15 (not including the limerock berm) removed 64% of the incoming P load. The percentage load reduction during the verification period was slightly higher, at 69%. Respective mass P removal rates during these periods averaged 2.1 and 6.5 gP/m$^2$-yr. The higher removal rate observed during the verification period was due to both higher hydraulic loadings, and higher influent TP concentrations.

### 5.2.2 Post-STA

Phosphorus load reduction by Cell 4 has been fairly consistent over the past six years. For the entire period of record (POR) (Feb. 95 – Sept. 01), Cell 4 removed 62% of the influent P load, at a mass removal rate of 1.65 gP/m$^2$-yr. During the model calibration and STSOC verification periods, P removal by Cell 4 averaged 73% (1.86 gP/m$^2$-yr) and 62% (1.93 gP/m$^2$-yr), respectively. Initially, STC-9 P removal performance was poor, but it improved with time. During the period of record, STC-9 removed only 15% of the inflow P (mass removal of 0.13 gP/m$^2$-yr). During the verification period, the P removal rate was much higher (41%, and 0.32 P/m$^2$-yr).

## 5.3 Compliance with Water Quality Criteria

### 5.3.1 Effluent Compatibility With Downstream Receiving Waters

As part of the STSOC effort, inflow and outflow samples from NTC-15, STC-9 and Cell 4 were collected and subjected to toxicity analyses. Hydrosphere Research performed the Test Cell toxicity assessments, and FDEP's laboratory performed the Cell 4 assessments. Analyses performed included the 7-day Chronic Static Renewal Screen Toxicity Test, the 96-hour Chronic Static Non-renewal Screen Toxicity Test and the 14-day Algal Growth Potential (AGP) Screen. Test cell effluent samples were collected at the outflow weir, which is after passage through the limerock berms and subsequent polishing segment of the wetland.

The 7-day Chronic Toxicity Test was performed using the bannerfin shiner, *Cyprinella leedsi*, and the waterflea, *Ceriodaphnia dubia*. Results for both organisms are summarized in Table 5-1. The

*C. leedsi* analysis utilizes four replicates per sample and the *C. dubia* analysis utilizes ten replicates per sample.

For *C. leedsi*, none of the samples produced an adverse effect. Similar results were observed with *C. dubia*, with the exception of the NTC-15 effluent sample, which displayed a slight adverse effect. The *C. dubia* and *C. leedsi* control group had acceptable survival ($\geq$80%) and reproduction (>15 neonates average per surviving female) for *C. dubia*. The analysis acceptability for average dry weight of surviving controls has not been established for *C. leedsi*.

**Table 5-1**. STSOC 7-day Chronic Toxicity Test results for *C. dubia* and *C. leedsi*

| | | ***Ceriodaphnia dubia*** | | ***Cyprinella leedsi*** | |
|---|---|---|---|---|---|
| Sample Date | Sample ID | Survival (percent) | Reproduction (Brood total) | Survival (percent) | Reproduction (Brood total) |
| 08/01 | Control | 100 | 37.1 | 100 | 0.60 |
| 08/01 | NTC-15 In | 90 | 31.1 | 100 | 0.64 |
| 08/01 | NTC-15 Eff | 90 | 29.9* | 100 | 0.61 |
| | | | | | |
| 09/01 | Control | 100 | 34.1 | 100 | 0.54 |
| 09/01 | STC-9 In | 100 | 34.0 | 100 | 0.57 |
| 09/01 | STC-9 Eff | 100 | 32.3 | 97 | 0.55 |
| | | | | | |
| 12/01 | Control In | 100 | 18.4 | 100 | 0.51 |
| 12/01 | Cell 4 In | 100 | 17.2 | 95 | 0.48 |
| 12/01 | Control Out | 100 | 16.7 | 97 | 0.56 |
| 12/01 | Cell 4 Out | 100 | 21.3 | 100 | 0.57 |

A “*” denotes a significant difference between the sample and the control for the observed endpoint.

The 96-hour Chronic Toxicity Test was performed using the microalga, *Selenastrum capricornutum*, in replicates of three. For this analyis, the control and samples were provided with a full suite of nutrients. No chelating agent was provided. All the test cell samples showed a significant decrease in growth except for NTC-15 influent (Table 5-2). Control samples and test samples were valid since results fell within acceptable limits ($\geq$2 x $10^5$ cells/mL standing crop in the controls; and variability of controls should not exceed 20%). The poor growth exhibited by the microalga on the NTC-15 effluent and the STC inflow and outflow waters may have been due to a micronutrient deficiency (caused by precipitation in the media), or perhaps due to inhibiting chemicals exuded by the SAV in the test cell. *Chara* is the dominant SAV species in STC-9 and NTC-15, and reportedly can have an allelopathic effect on microalgae.

The control sample for the Cell 4 influent sample failed to meet the minimum growth requirement (1.0 x $10^6$ cells / ml) and was therefore invalidated; however, as shown in Table 5-3, no toxicity was indicated from the algal growth in the 100% sample portion of the *S. capricornutum* analysis for Cell 4 influent.

**Table 5-2.** STSOC 96-hour Chronic Toxicity Test results for *S. capricornutum*.

| Sample Date | Sample ID | Cell Standing Crop (cells/mL) | Standard Deviation (cells/mL) |
|---|---|---|---|
| 09/01 | Control | 1.01 x $10^6$ | $\pm$1.57 x $10^5$ |
| 09/01 | NTC-15 In | 9.02 x $10^5$ | $\pm$9.29 x $10^3$ |
| 09/01 | NTC-15 Eff | 4.71 x $10^5$* | $\pm$1.85 x $10^5$ |
| 09/01 | STC-9 In | 2.10 x $10^5$* | $\pm$2.78 x $10^4$ |
| 09/01 | STC-9 Eff | 3.24 x $10^5$* | $\pm$3.19 x $10^4$ |
| 12/01 | Control In | 6.43 x $10^5$** | |
| 12/01 | Cell 4 In | 1.02 x $10^6$ | |
| 12/01 | Control Out | 1.02 x $10^6$ | |
| 12/01 | Cell 4 Out | 1.83 x $10^6$ | |

A "*" denotes a significant difference between the sample and the control for the observed endpoint.
A "**" denoted a control sample that failed to meet the minimum growth requirement of 1 x $10^6$ cells / ml.

Finally, an algal growth potential (AGP) bioassay assessment was performed on the influent and effluent for Cell 4, and the NTC-15 and STC-9 test cells. Using *Selenastrum capricornutum*, none of the 14-day AGP test cell samples demonstrated any significant growth (Table 5-3). In the Cell 4 influent sample, nitrogen (N) reportedly was the limiting nutrient and in the Cell 4 effluent sample, N and P were found to be co-limiting nutrients. Maximum standing crop concentrations represent an average of three replicates per sample for the test cells. Replicate data for the Cell 4 analyses were not provided by the laboratory.

**Table 5-3.** STSOC results of algal growth potential bioassay. There were no significant increases between the sample and the control for the observed endpoint.

| Sample Date | Sample ID | Mean Maximum Standing Crop mg/L | Standard Deviation mg/L |
|---|---|---|---|
| 08/01 | Control | 33.3 | $\pm$36.2 |
| 08/01 | NTC-15 In | 23.3 | $\pm$5.8 |
| 08/01 | NTC-15 Eff | 8.3 | $\pm$7.6 |
| 08/01 | STC-9 In | 0 | $\pm$0 |
| 08/01 | STC-9 Eff | 0 | $\pm$0 |
| 09/01 | Control | 68.3 | $\pm$22.5 |
| 09/01 | NTC-15 In | 5.0 | $\pm$5.0 |
| 09/01 | NTC-15 Eff | 11.7 | $\pm$12.6 |
| 09/01 | STC-9 In | 8.3 | $\pm$2.9 |
| 09/01 | STC-9 Eff | 3.3 | $\pm$5.8 |
| 12/01 | Control In | Not applicable | |
| 12/01 | Cell 4 In | 7.4 | |
| 12/01 | Control Out | Not applicable | |
| 12/01 | Cell 4 Out | 0.4 | |

From these analyses, there is no reason to suspect an adverse effect to downstream waters from the effluent of a full-scale SAV-LR treatment wetland. The 7-day Chronic Toxicity Tests with *Cyprinella leedsi* and *Ceriodaphnia dubia* revealed no adverse effects between influent and effluent waters for any of the SAV/LR standard of comparison platforms. Furthermore, the results of the Algal Growth Potential Screen demonstrate that the SAV wetlands reduce the eutrophication potential of runoff waters by removing nutrients that cause excessive plant growth.

In concert with the toxicity assessments, all samples also were analyzed for organonitrogen and organophosphorus pesticides, and chlorinated herbicides. Ametryn and atrazine pesticides were detected, at low concentrations, in the inflow and outflow waters of Cell 4, NTC 15 and STC-9. No other pesticides or herbicides were detected.

### 5.3.2 Class III Water Quality Criteria

Since any SAV/LR system built will ultimately discharge into downstream receiving waters, water quality from these treatment cells must meet the FDEP Class III water quality standards. The data gathered during the STSOC verification period in NTC-15, STC-9 and Cell 4 are provided in Section 3. The mean effluent concentration for each parameter met the water quality standards, with only two exceptions.

First, the mean Cell 4 effluent dissolved oxygen concentration (DO) averaged 4.0 mg/L, slightly below the permitted level of 5.0 mg/L. By contrast, DO increased dramatically within the wetlands of the two test cells, from < 0.5 mg/L in the inflow to > 5.0 mg/L in the outflow waters. Test cell "pre-berm" pH values caused a second excursion, since according to the Class III water quality standards the pH should not increase by more than one pH unit from background levels. The south test cell pre-berm effluent average pH of 8.56 was 1.09 pH units above that of the influent water. The test cell outflow, however, exhibited a lower mean pH (8.25), demonstrating the effectiveness of the outflow region limerock berm in moderating effluent pH levels.

*Mercury in SAV/LR Systems*

The potential effects of the STAs on mercury cycling has been a concern due to the high mercury levels detected in sportfish caught in the Everglades system. Wetlands such as the STAs are being scrutinized because of their ability to support sulfate-reducing bacteria that appear to carry out mercury methylation.

Assessments for mercury have been performed in numerous research and full-scale platforms in STA-1W. The most rigorous direct assessment of SAV/LR systems was performed on our

Phase I mesocosms that received Post-BMP waters. This effort revealed that SAV/LR systems do not increase either total mercury or methyl mercury concentrations (Rawlik, 2001).

Mercury sampling also was performed on NTC-15 and STC-9 from 8/23/01 to 9/20/01. Test cell outflow samples exhibited lower total mercury and methyl mercury concentrations than inflow samples. This evaluation also found no evidence for increased mercury concentrations in mosquitofish collected from the test cells (Rawlik, 2001).

## 5.4 Cost-Effectiveness of Technology

A summary of costs for the various SAV/LR conceptual designs is provided in the preceding section. The present worth cost for an "optimized" combination (Post-BMP + Post-STA) SAV/LR system that meets an outflow concentration of 14 µg/L, with 0% bypass, is $23,537,214 (without STA-2 costs). Including STA-2 costs in this analysis increases the present worth cost to $186,339,555. Omitting the STA-2 costs, the cost of removing P on a "per pound" basis (assuming outflow TP of 14 µg/L with 0% bypass) is $9/lb for the SAV/LR system.

The STSOC Post-BMP and Post-STA designs, using assumptions of poorer hydraulic performance, result in different footprint requirements and costs. For the STSOC Post-BMP wetland used to reduce TP levels from 122 to 26 µg/L with 0% bypass, the present worth cost (without STA-2 costs) is $4,167,704. For the STSOC Post-STA wetland used to reduce TP levels from 50 to 20 µg/L with 0% bypass, the present worth cost (without STA-2 costs) is $72,933,064.

The assumptions on which these costs are based are numerous. Some assumptions pertain to modeling (e.g., were the calibration data sets representative?), others pertain to hydraulic processes (e.g., will filling farm canals and adding level spreaders actually increase efficiency?), and finally, other assumptions are ecological and performance-related (at the full-scale, will SAV thrive and provide treatment throughout most of an STA footprint?). These and other questions remain unanswered, but are important to address in moving forward with deployment of the SAV/LR technology in the STAs.

## 5.5 Implementation Schedule

We have developed an estimate of the time required to implement a full-scale SAV/LR system, which under most design scenarios essentially entails an internal retrofit of STA-2. Implementation time will be dependent upon many factors, including feasibility of construction methods, engineering and construction plan development and approval, permitting, bidding and contracting. However, the following is an estimate of the time required to implement the optimum design scenario given the conceptual level of detail included in this cost estimate:

<u>Optimum Design Schedule – Change Vegetation, and Deploy Limerock Berms and Lateral Deep Zones in STA-2.</u>

| | **Time** | **Start Month – End Month** |
|---|---|---|
| Engineering design; final construction methods selection | 2 months | 0 – 2 |
| Final engineering and preparation of design plans and specifications; hydraulic modeling | 9 months | 3 – 12 |
| Bidding and contractor selection | 3 months | 9 – 12 |
| Dewatering of STA-2 and time for sediment consolidation | 6 months | 6 – 12 |
| Construction, assuming 7 berms constructed at 400 ft of berm / day | 12 months | 13 – 25 |
| Startup – eradication of invasive species and establishment of SAV | 12 months | 26 – 38 |

Following the startup period described above, an additional 1 – 3 years likely will be required to achieve a fully functional SAV wetland. The duration of this startup period will depend on the existence of a suitable SAV inoculum within the footprint, on antecedent P levels in the soil (i.e., residual fertilizers) and on the location along the inflow – outflow gradient (i.e., a Post-BMP wetland will achieve outflow goals sooner than a Post-STA system). Outflow TP concentrations in the range of 25 µg/L therefore should be attainable in 12 months (50 months after project start date), and outflow TP levels of 14 µg/L should be attainable within 36 months (74 months after start date).

## 5.6 Feasibility and Functionality of Full-Scale Design

With STA-1W Cell 4 (147 ha) and Cell 5b (930 ha), the District has demonstrated that construction and maintenance of SAV wetlands is feasible at the STA scale. Long-term functionality also has been demonstrated, since Cell 4 has proven to be robust and effective in removing TP down to levels of 14 µg/L.

Before further implemention of SAV wetlands takes place in the STAs, however, several critical factors need to be addressed. These are as follows:

- the sustainability and P removal effectiveness of SAV wetlands used for treating Post-BMP waters (waters with higher inflow TP levels than Cell 4) should be verified at an operational scale
- the performance benefits that our model indicates can be achieved through hydraulic improvements (farm canal plugging and limerock level spreaders) should be verified at an operational scale
- the possible detrimental effects of pulsed hydraulic loadings, with respect to stagnation and high peak loadings, should be assessed at an operational scale
- because water availability will strongly influence the ability to deploy SAV at an operational scale (and also influence the resulting SAV footprints), factors that influence water budgets (e.g., seepage, potential water availability during droughts) should be quantified for each STA
- large-scale evaluations of drydown and reflooding on SAV sustainability and performance should be performed
- hydrilla is proving to be an effective competitor in full-scale SAV communities. Its P removal performance therefore should be quantified.
- our findings on SAV performance (all performed at STA-1W) may not be transferable to the other STAs, due to basin-specific differences in soils and inflow water chemistry (e.g., P speciation, calcium content). Key biogeochemical and ecological factors that can influence SAV sustainability and performance should be addressed for each STA

## 5.7 Operational Flexibility and Sensitivity to Fire, Flood, Drought and Hurricane

SAV desiccates and decomposes rapidly, so it should not provide fuel to support a wildfire in the event of extreme drydown. Water storage in a SAV-based STA will be comparable to that of existing STA designs. Therefore, no flood damage is anticipated, and depending on the timing of water pulses, the SAV wetland may actually provide some floodwater storage. Due to the submerged nature of the vegetation, hurricane damage to an SAV system likely will be less than that to an emergent macrophyte-based STA. The limerock level spreaders proposed in the optimum design would be particularly helpful in reducing wave runup and internal currents during extreme wind events. There are anecdotal reports of SAV communities being uprooted during hurricanes, but this is only likely in large, non-compartmentalized water bodies.

SAV systems are susceptible to drought, and based on our only data (mesocosm-scale), the recovery period for an SAV community is likely to be at least four to six weeks. By contrast, drydown is likely to be a key strategy for consolidating sediments at the front-end of any vegetated STA community. Moreover, based on our mesocosm findings, sediment P export following rehydration of the SAV systems does not appear excessive.

## 5.8 Residual Solids Management

Vegetation harvesting will not be implemented in full-scale SAV wetlands, so there will be no residuals that will require management. Large amounts of marl sediments will accrue over time in SAV wetlands, particularly in the inflow region of the STA, but we anticipate that drydown and consolidation will be a key management technique to maintain freeboard in the wetland.

# Section 6: Summary of Full-Scale SAV/LR Implementation Issues

The existing sustainability and performance information on SAV/LR systems demonstrates that this technology is quite promising. Much of the key data related to the SAV/LR technology has been obtained from STA-1W Cell 4. This wetland has been by far the most useful platform for obtaining critical data, due to its large size, long-term performance record and hydraulic behavior.

The list of information needs in moving forward with the SAV/LR technology is long, and is provided above in Section 5.6. To provide a suitable platform to address several of those topics, we believe it is prudent to undertake another scale of assessments.

We propose that the District utilize the STA-1W western flow path (Cell 2 – Cell 4) to provide a “Proof of Concept” demonstration of the effectiveness of hydraulic improvements (level spreaders), and of the performance and sustainability of large-scale SAV communities for Post-BMP treatment. Several factors make the western flow path ideal for this approach:

- Our PMSAV model predicts that dramatic benefits can be achieved from hydraulic improvements, particularly for a Post-BMP SAV wetland. The scale of the western flow path is appropriate (with respect to variations in flows, depths and velocities) for evaluating these structural enhancements.

- The outflow region of Cell 4 currently has stable, mature sediments. If the runoff P concentrations and loads that are fed to Cell 4 can be better attenuated, the wetland should provide lower outflow P concentrations. This will help define the lower concentration limits attainable by SAV wetlands.

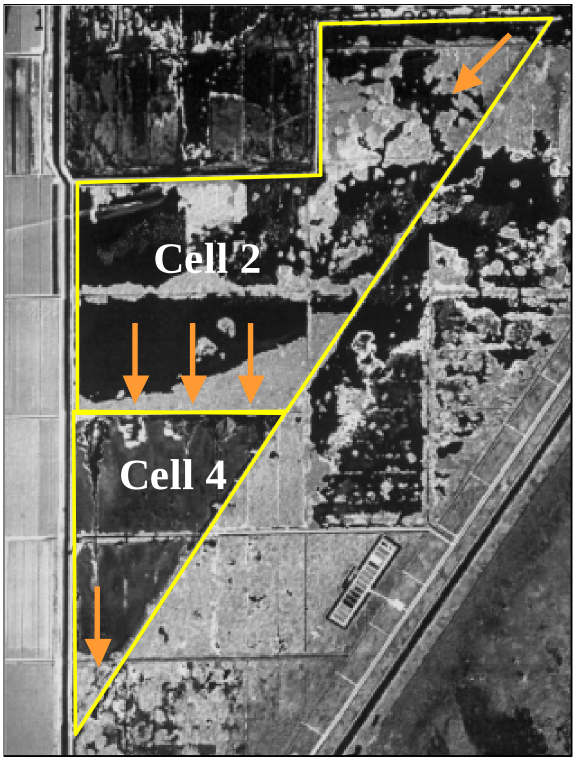
- Cell 2’s performance currently is poor. During the STSOC verification period, this 440 ha wetland exported, rather than removed P.

- We currently have extensive hydraulic and performance information for both Cells 2 and 4. This information will enable us to accurately assess the effectiveness of the suggested modifications, from both a P removal and hydraulic performance basis.

A schematic of potential modifications to the western flow path is provided in Figure 6-1. Modifications would include some plugging of farm canals, elimination of emergent vegetation in selected regions of Cell 2, and hydraulic modeling, design and deployment of limerock level spreaders in Cells 2 and 4.

As a final note, we did not address the incorporation of flow equalization basins (FEBs) in this conceptual analysis. This is an approach that potentially can provide two benefits, namely attenuation of flow peaks, and providing a source of water for the downstream SAV community during potential stagnant or drydown conditions. Depending on site-specific conditions (e.g., seepage rates, potential allocation of water during droughts), an FEB may need to be an integral component of selected STAs. We suggest that it is not unreasonable to expect that a FEB could be situated in the inflow region of the STA (first 25 to 33% of the footprint), particularly if strategies can be developed that enable them to provide a moderate amount of P removal.

While FEBs potentially could be a component of the STAs, it is our view that it is more important first to address potential benefits achieved from internal hydraulic improvements and deployment of SAV further upstream in the wetlands.




Existing Cell 2 &
Cell 4 Configuration

Direction of Flow

Suggested Modifications

1) Hydraulic Improvements
   - Plug relic farm canals
   - Limerock “level spreaders” (possible locations)

2) Vegetation Improvements
   - Eliminate emergent vegetation to encourage SAV proliferation

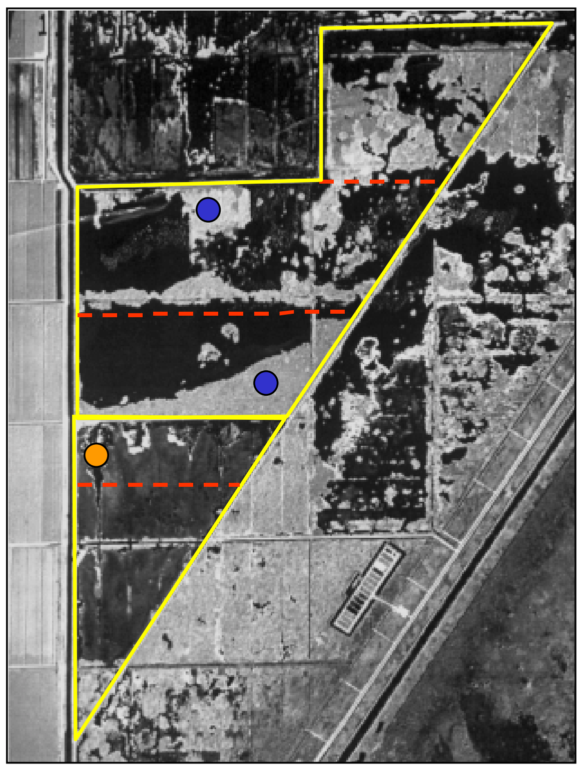


**Figure 6-1.** Proposed “proof of concept” demonstration of SAV technology.

# Section 7: References


Box, G.E.P., Hunter, W.W., and J.S. Hunter. 1978. Statistics for Experimenters. John Wiley and Sons, New York, NY.

Chimney, M.J., M. Nungesser, J. Newman, K. Pietro, G. Germain, T. Lynch, G. Goforth and M.Z. Moustafa. 2000. Stormwater treatment areas – status of research and monitoring to optimize effectiveness of nutrient removal and annual report on operational compliance. Everglades Consolidated Report, South Florida Water Management District, West Palm Beach, FL. P. 6-1 – 6-127 [Chapter 6].

DBE. 2002. Demonstration of Submerged Aquatic Vegetation/Limerock Treatment Technology for Phosphorus Removal from everglades Agricultural Area Waters: Follow-On Assessment. Final Report prepared by DB Environmental, Inc. for the South Florida Water Management District and Florida Department of Environmental Protection, West Palm Beach, FL.

Kadlec, R.H. and R.L. Knight. 1996. Treatment Wetlands. 893 pp. Lewis Publishers, Boca Raton, FL.

Kadlec, R.H. 2001. Detention time distributions – So What? Draft memorandum prepared for U.S. Department of Interior.

Rawlik, P. 2001. Evaluation of Advanced Treatment Technologies for Mercury Effects: SAV/LR. Unpublished report. South Florida Water Management District, West Palm Beach, FL.

Reed, S.C., Middlebrooks, E.J. and R.W. Crites. 1988. Natural Systems for Waste Management and Treatment. McGraw-Hill Book Company. New York, NY.